THE INTERNATIONAL WINE SUPPLY CHAIN: CHALLENGES FROM BOTTLING TO THE GLASS

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THE INTERNATIONAL WINE SUPPLY CHAIN: CHALLENGES FROM BOTTLING TO THE GLASS

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To Francisca, Panchito and Josefina.

No words can tell how grateful I am.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

This thesis focuses on two important challenges for the wine supply chain: the international shipping temperatures and their effect on the perceived quality of the wine, and the optimization of the bottling schedule for a large winery.

The first challenge is important because the wine maker takes special care in producing the best quality product, which is then shipped to the importer/distributor or consumer, generally in non-refrigerated containers at the mercy of the prevailing environmental conditions. As Robert M. Parker, a known wine advocate points out: "It is a frightening thought, but I have no doubt that a sizable percentage (between 10% and 25%) of the wines sold in America have been damaged because of exposure to extremes of heat". One of the contributions of this work is that it is the first to measure, for a significant period of time, the temperatures along the international wine supply chain and to link them to the specific supply chain processes (transshipment of containers or use of thermal liners). This is also the first work that analyzes the effect of shipping temperature on the perceived quality of the product by those who make the purchase decision for importers, restaurants and supermarkets.

First we documented and tracked the wine shipping temperatures, to detect extreme temperatures. We tracked the temperature of the container at the different stages of transport: winery to port, at sea, transshipment, and from port of destination to importer/distributor. We also analyzed the temperature patterns in 3 dimensions: first, the temperature to which the wine was exposed; second, for how long the wine had been exposed to those temperatures, and finally, the cumulative effect, which is described by the Arrhenius equation that describes the relation of

temperature to the speed of the chemical reactions. The results show that wine shipments are very often exposed to high temperatures for extended periods of time. We also show that the exposure to high temperatures can be reduced by avoiding the transshipment phase and by minimizing the time spent at the destination port to importer/distributor stage, especially in the summer season.

We then quantified the effect of thermal liners on container temperatures. The results show that the liner is effective in buffering the external temperature and reducing the daily temperature range.

To determine the importance of reducing the exposure to high temperatures, we analyzed the effect of shipping temperature on the perceived quality of the product by the institutional consumer. Blind tasting experiments were performed with consumers of wine who are in charge of deciding which wine to buy for their institutions. Each of them had 3 glasses of wine to taste that randomly contained wine that had either been kept under controlled conditions or had been subjected to shipping temperatures. We then asked them three questions: Which glass, if any, tastes different from the others? Which glass(es) tastes better? In your opinion, which glass(es), if any, hold wine that was subjected to shipping temperatures? The results showed that for white wines, tasters were able to detect differences between the wines that had been exposed to shipping temperatures and that they preferred them. For red wines, they were unable to detect any differences.

Our contribution to the second challenge was the development of a model that produces solutions for the wine bottling lot sizing and scheduling problem with sequence dependent setup times, in an adequate time-frame, which can be implemented by large wineries. The model incorporates particular aspects of the wine bottling problem such as: major/minor setups, sequence dependent setup times, crewing limitations and finally, sanitation and traceability constraints. Also, using a bicriteria approach, previously used by Ehrgott and Ryan (2002), we introduce a robust schedule approach.

Finally, we implemented an effective decomposition algorithm that uses the structure of the problem, to produce good solutions that can be applied to other families of sequence dependent scheduling and lot sizing problem. We use the major/minor setup structure to decompose the problem into a two-stage iterative optimization problem. This decomposition approach allows us to parallelize the optimization, which significantly reduces the solution time. Our computational results indicate that the model achieves reductions of 30% in the total plan costs with respect to their current plans. The introduction of demand and capacity robustness produces solutions that are stable and greatly reduces the need of rescheduling in the case of momentary line breakdowns or the appearance of emergency order. Introducing this robustness does not significantly increase the optimal plan costs. Finally, we present a visualization and solution intervention decision support system that is currently being implemented by a large winery.

CHAPTER I

INTRODUCTION

"Truth comes out in wine."

– Pliny the Elder

The international wine supply chain is a complex and dynamic system. The complexity is due its biological origin, production characteristics and the distance from the production and the consumption in term of distance and tiers. There are a number of interesting research issues in the international wine business, that range from the areas of logistics and operations to marketing science [84]. There has been some research on the application of logistics and operations science to the wine business, which has looked at different aspects such as the scheduling of the grape harvesting operations [18, 46] to the use of postponement strategies [26], to a real-time risk control and monitoring system for incident handling in wine storage [63]. But there has not been any effort to study the international wine supply chain as a whole and how the transport conditions affect the quality of the product.

Wine has a complex production process and supply chain because: the product is affected by the surrounding environmental conditions, evolving from the moment it was bottled; it is produced in locations that are distant from its consumption and sometimes on opposite hemispheres, which involves long transport distances and time; wine is differentiated into multiple segments or wine classes [34] and has a very complex purchase pattern that is affected by factors such as country of origin and medals [67]; and finally, wine is considered a drug, which leads to governments imposing conditions and restrictions on its commercialization. As an example of the conditions that governments impose on the commercialization of wine, after the end in 1933 legislators in the US passed the Twenty-first Amendment of the Constitution which controls the sale and transportation of alcoholic beverages. In this amendment the law makers established a structure for supply chain of alcohol. Producers of alcohol could not sell their products directly to consumers, and should sell their products to licensed wholesalers, which in turn must sell to licensed retailers, which sell to the consumer [10]. This supply chain structure is called the “three-tiered” system. All of these factors render the supply chain and logistics of wine to the US a challenging endeavor and an interesting subject of research for logistics and operations.

Complexity can be reduced by helping the agents in the supply chain make better decisions regarding the international transport of wine. The first step is to understand the conditions to which the product is subjected during its transport from the winery to the consumer. Specially the temperature to which the product has been exposed, because researchers have shown that wine characteristics are directly dependent on the temperature level and time [100]. By documenting the temperature during the international transport and analyzing their effect on the perceived quality of the product, can help in this decision process. To keep costs low, wine is mostly transported in non temperature controlled containers, leaving the product to the mercy of the surrounding temperature conditions, which in the Equator can reach over 35 °C. This situation can affect the changes and evolution of the product as it moves along the supply chain and time passes. Transport decisions range from: first, the use of a refrigerated container or a dry container; second, the choice on the time and the route to ship the product and third, the use of thermal insulation in the container. These decisions have economical implications for the winery, in terms of the quality of the final product and the transportation costs, and are currently being made using historical information and their own experience without any scientific evidence.

Another challenging problem for large wineries is the decision to bottle their wine and the sequencing of their bottling lines to cover the demand of their customers. The complexity of the problem lies first in the number of Stock Keeping Units (SKU) that a large winery has and needs to schedule for any given planning period, which can be over 200. Next, this large number of SKUs need to be lot-sized and scheduled over a number of bottling lines. The number of bottling lines can be over 10 and they can differ in their capacity and the types of products that can be bottled. Another complexity is that the planner needs to take into account setup times that depend on the product that was previously bottled. This is because the time need to setup and clean the line is different if a red wine is bottled first and then a white wine, or if a white wine is bottled first and then a red wine. Finally, the plan needs to take into account constraints related to the availability of crews and the length of the production shifts.

The complexities of the wine bottling problem are reflected in the efficiency of the bottling lines in the wine industry, measured as the total production divided by the capacity of the line. This efficiency is on the order of 30% to 45%, so for 70% to 65% of the time, the line is either in setup, stopped or idle. This is an indication that there is space for improvement.

The first part of this research documents the temperatures patterns to which the wine is subjected during its international transport to the US and analyzes the danger of exposure to extreme temperature. Also, we determine the effect of using thermal insulation in buffering the internal temperature of the container. Finally, we performed tastings experiments to analyze the effect of transport temperature patterns on the quality of wine as perceived by people who make the purchasing decisions.

In the second part we will analyze the problem of bottling the wine and sequencing of the lines to meet customer demand. Our objective is to solve in reasonable time the bottling lot sizing and scheduling problem of a large winery. We present a formulation and decomposition approach for the lot sizing and scheduling problem for parallel lines with sequence dependent setup times, using the case of a large winery. We will also present some approaches for finding robust solutions. Finally, using the decomposition and parallelization, we show that we can significantly reduce the solution time.

CHAPTER II

SHIPPING TEMPERATURES

2.1 Introduction

Wine is a living organism that evolves with time and is directly affected by the surrounding conditions. The wine maker takes special care in maintaining controlled conditions to protect the product. At the other end of the supply chain the consumer takes special care of the product by storing it under controlled conditions. However, what happens to the product en route to the consumer? To what conditions has the product been subjected during this period of time? Have these conditions changed the perceivable characteristics of the product? Robert M. Parker, a widely known wine advocate and wine writer, writes [89, p. 23]:

> *"It is a frightening thought, but I have no doubt that a sizeable percentage (between 10% and 25%) of the wines sold in America have been damaged because of exposure to extremes of heat."*

It is widely known that excessively high temperatures can produce rapid deterioration and color changes in the wine [51, 54, 81, 85, 86, 93]. Studies have shown that the level of change in the wine characteristics are directly dependent on the temperature level and time during which the wine has been exposed [100].

Production areas of the *"new world wines"* (Australia, Argentina, Chile and South Africa) are located in the southern hemisphere, at a considerable distance from the major consumer markets (North America and Europe) in the opposite hemisphere. Consequently the majority of wines coming from these regions have to endure long periods of travel with temperatures that can go over 45 °C.

According to oenologists the optimal temperatures for storing white wine is between 13 °C to 15 °C, and for red wines, 10 °C to 20 °C [19]. A study [21] has shown that during summer months, wines traversing hot geographic locations are frequently exposed to temperatures above 24 °C, and often for extended periods of time. Furthermore there may be large variations of temperature throughout a container at one given time.

We have observed that in most cases the freight forwarder uses the least cost route to send the containers, without much regard to the danger of extreme temperature exposure, which can affect the quality of the product. The transport is mostly done in non refrigerated trucks or containers, risking exposure to external climactic conditions, including those incurred when crossing the equator. There is a number of papers which report temperatures during international wine shipment, but still there is no widespread knowledge or tool available for the winemaker or importer/distributor to make an informed decision on the temperature of the shipping route that will be used for the product.

There are two objectives in the analysis of the temperature during transport, the first one is to describe the temperature patterns along the South to North international wine supply chains and quantify the danger of extreme temperature exposure, while providing general recommendations to reduce the temperature danger in wine shipments. The second objective, which will be covered in a subsequent chapter, is to analyze the effect of the shipping temperatures on the perceived wine quality, which extends the work of [22]. The quality effect will be analyzed by performing a number of tasting experiments with the people of the trade, to determine if the international shipping temperature patterns have any effect on the quality of the product as perceived by customers, including importers, distributors, and sommeliers.

We will first review the previous research related to the effect of temperature over wine during shipping or storage conditions and also the different dangers to which the wine can be exposed during transport. This chapter will also define our measures of temperature danger. The next section, will present results for the different risk or danger measures for the aggregated data and two periods of the year (June-Sept and Dec-March). In the next chapter, by correlating the temperature data with the tracking of the containers we can determine the relative temperature danger of each phase of transport and time of year. Finally, will provide general recommendations to reduce temperature danger while shipping wine.

2.2 Literature review

Prior work on documenting shipping temperatures scarcely rises from anecdotal. The research by Butzke et al. [22] is the most comprehensive documentation of temperatures during wine transport, but was conducted only for domestic distribution within the US. Butzke et al. recorded 26 individual shipments, containing a total of 47 recording devices, departing from the winery warehouses in California to 13 different destinations within the USA and measured the ethyl carbamate, a byproduct generated in wine by exposure to extreme temperatures. They concluded that there is a higher concentration of ethyl carbamate in the wines exposed to extreme temperatures.

Reports by [74] and [110] are the only ones that record international shipping temperatures. The first reported maximum temperatures of 48 °C in shipments from South Africa to Finland. The second, reported temperatures of bottled and bulk shipments of wines, from South Africa and New Zealand to different destinations, with maximum temperatures of 28 °C. These reports use a small sample, of less than 10 tracked shipments, and do not span a sufficient period of time to account for seasonal effects.

Our contribution is to greatly expand the scale and scope of these studies by documenting shipping temperatures from many international origins to the US and to correlate the temperature with the different transport phases that the container travels along the international wine supply chain. The collected data is significant in number and spans over several years so that the danger may be more reasonably estimated.

Temperature has a significant effect on the chemical and organoleptic characteristic of wine [36, 39, 54, 85, 90]. As an example, Robinson et al. [95] performed chemical and tasting panel analysis of wines exposed to extreme temperatures and also tried to replicate shipping temperatures by keeping a case of wine in the trunk of a car for a couple of weeks. They concluded that the wine suffered chemical changes and, with an expert tasting panel composed of oenologists, determined that those changes were reflected in the taste of the wine. But there is a question of whether the patterns they used are representative of real shipping conditions and also, if the tasting panel results (composed mostly by oenologist) can be comparable to the results obtained by a panel composed by expert consumers or commercial buyers. They are the ones who select the wine that the consumer will purchase, so any quality issue that influences their tasting experience can affect the winery access to the market.

There are other factors that can affect the chemical and organoleptic characteristics of the wine during transport, such as: humidity [68], vibration [27] and light [14]. However temperature is still the most significant factor affecting the characteristic of the wine [22]. Since, as described by the Arrhenius equation, the rate of any chemical reaction rate increases exponentially with the temperature [33]. To determine and analyze the effect of temperature on the product, we will focus on three aspects: the level of exposure to extreme temperatures, the amount of time that the product was exposed to that temperature and the cumulative effect.

Exposure to extreme temperature is not always considered detrimental to the quality of the wine. In some types of wine, they are intentionally exposed to high temperatures to produce chemical and taste profile changes. That is the case of the

Madeira wine producers, who use a baking process known as *estufagem* in production of the wines [23].

2.3 International wine supply chains

Most of the wine that is transported internationally, is moved in dry containers by truck, vessel or train. Figure 1 lists the different phases of the container during shipping: Winery to port of origin, at-sea, transshipment and from destination port to importer.

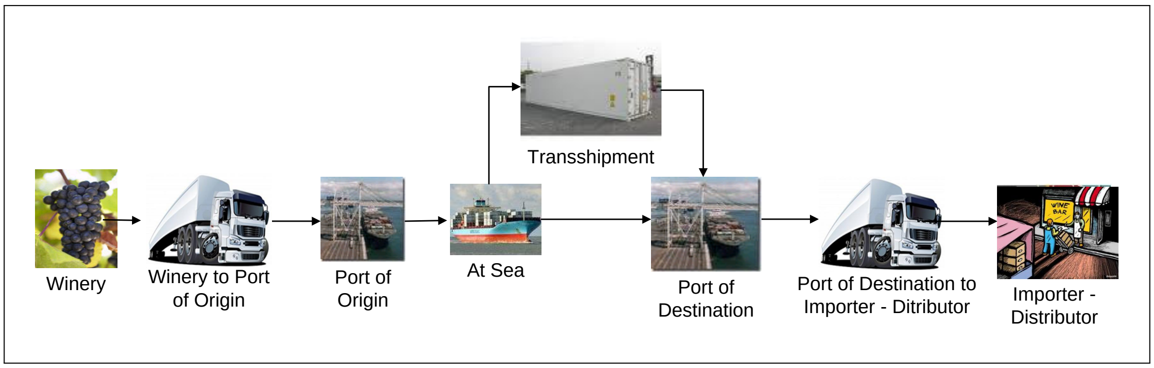


Figure 1: Common stages in international wine supply chains: Winery to port of origin, At Sea, Transshipment, Port of destination to importer/distributor.

The first stage, winery to port of origin, covers the movement of the container from the winery until it has been loaded into the vessel. At this phase the container is loaded with the cases of wine, either at the winery or at a consolidation point. Once the loading has finished, the container leaves on a truck to its port of departure. The length and route of this trip varies according to how close the winery or consolidation point is from the port. For example, for the case of Argentina, the trip from Mendoza (production area) to the departure port of Valparaiso or San Antonio (located in Chile) takes the truck over a road that crosses the Andes mountain range, which can take several hours or even days to cross. Once the container has arrived to the departure port, it is set on a stack waiting to be loaded on the vessel.

The at-sea phase lasts from the moment the container is loaded in the vessel until the container is unloaded at the destination port. The location of the container in the vessel is chosen to optimize the loading and unloading process of the ship, so the container can be placed in the belly of the ship under the buoyancy line, over the deck surrounded by other containers or even on the top or side of the stack where it will receive direct sunlight. To avoid exposure to sunlight and extreme temperatures, wineries request their freight forwarders to ask that their containers be set under the deck, below the buoyancy line. Unfortunately the shipowner may ignore such requests and evidence suggest that this is often the case [109]. A normal clause in the Bill of Lading states: "Steamer has liberty to carry goods on deck and shipowners will not be responsible for any loss, damage, or claim arising therefrom" [109]. From the point of view of the shipping lines, any customer who is concerned about the temperature of the cargo should use a refrigerated container (which can cost as much as three times the shipping cost of a regular dry container).

The transshipment phase—if present—starts when the container is unloaded from the vessel at a relay port. For the main routes from the southern to the northern hemisphere, the transshipment ports are generally located near the equator and so they have tropical temperatures. Transshipment times can vary from a couple of days to sometimes weeks, depending on the shipping company and route chosen. During this time the container waits in a yard, stacked with other units and exposed to the elements, until picked up and loaded on the vessel.

The fourth and final phase is from the port of destination to the warehouse of the recipient, whether be an importer, distributor or retailer. This phase starts at the moment when the container is unloaded in the port of destination and extends until the receiver opens the container. When the container is unloaded, it generally stays for a couple of days, waiting stacked in the port. Then it is transported on a truck, train or a combination of both to its recipient within the US. At this stage the container may be exposed directly to the sunlight and the high summer temperatures common in some areas of the US. Finally when it arrives at its destination it can be either unloaded immediately or be left in the yard to wait for unloading, prolonging its exposure to the ambient temperature and direct sunlight.

To track the temperature during the transport process we start at the winery (in either Argentina, Australia, Chile or South Africa) were they attach a pre-stamped envelope, which has a temperature recording device inside, to a pallet of wine that is shipped in a container to the United States. The envelope is finally recovered either at the importer, distributor or retailer level and is mailed to us. Once the envelope arrives, we are able to recover the temperature information from the recording device and relate this information with the tracking of the container, obtained from the shipping company. In Appendix A.1 there is detailed explanation of the process.

2.4 Temperature danger during transport and its measurement

Figure 2 shows an example of a typical wine shipment temperature profile coming from the southern hemisphere to the US at its different transport phases: At the winery to port, transshipment, and destination port to importer/distributor phases. We can observe temperature ranges that can go between 10 °C and 45 °C. The daily temperature variations, specially at the transshipment phase, are due to the day and night temperature variations at each location.

There are differences between the different transport phases, specially in the temperature levels and fluctuations. They tend to be more extreme in the transshipment phase because this process generally takes place in ports located near the equator, where temperatures are higher. During the at-sea phase, the typical pattern is a steady increase in temperature without any major daily fluctuations. Assuming the container is either below deck or covered with other units, and so insulated from big temperature fluctuations. The occasional dramatic exception is when the container is placed on the top, in which case there will be extreme temperatures spikes every day.

The steady increase is due to the movement of the vessel from the southern hemisphere to the equator, where the wine producers are at the end of the winter season in a Mediterranean weather, to the northern hemisphere, where the wine importer are at the end of the summer season. The winery-to-port and destination-port-to-importer or distributor phases tend to be very variable and generally depend on how the container is handled and on the season.

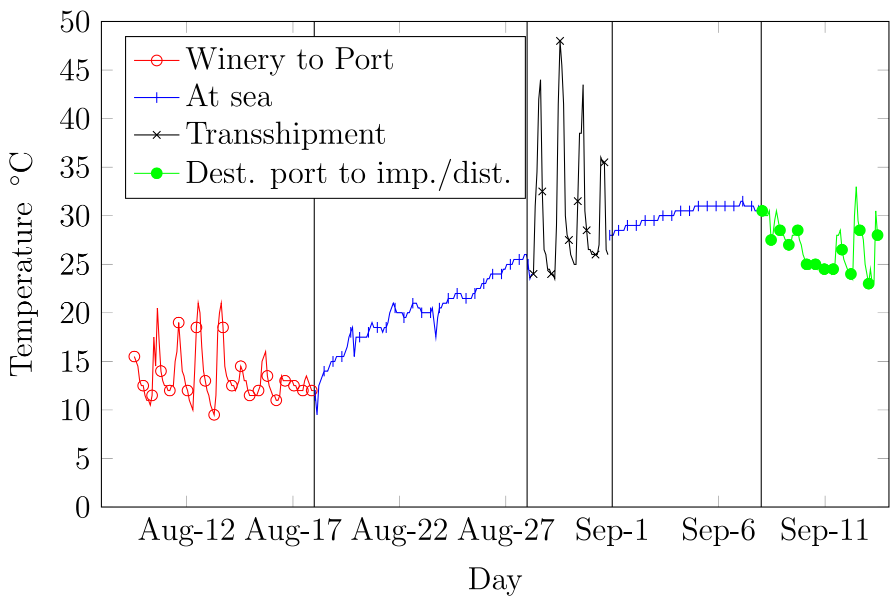


Figure 2: Example of tracked temperature and location.

Looking at this example, the temperature levels go beyond what can be considered optimal for the storage of wine. As Robinson et al. [95] concluded, the exposure to high temperatures will induce chemical and organoleptic changes in the wine, so it is expected that the product should be affected. To estimate the temperature danger during the transport we will analyze three aspects: first, the occurrence of a certain temperature level during transport; second, the amount of time or level of exposure, at a certain temperature level, to which the wine has been exposed to; and third, the cumulative effect of temperature during transport.

To analyze the effect of temperature we need first to understand how heat is transferred from the environment to the inside of the container and finally to the wine. Heat is transferred in three ways: conduction, convection and radiation. We are mostly concerned about conduction, which is the transfer of heat between two objects that have a differential of temperature, in this case between the air and liquid inside the bottle. Conduction is governed by the Fourier Law of thermal conduction ($\overrightarrow{q} = -k\nabla T$), which in its differential form indicates that the local heat flux density, $\overrightarrow{q}$, is equal to the product of thermal conductivity, k, and the negative local temperature gradient, $-\nabla T$ [32]. The heat flux density is the amount of energy that flows through a unit area per unit time. So the temperature that the wine will reach will depend first, on the temperature differential between the environment and the liquid; second, on the thermal conductivity of the materials: air, glass and water and third, on the amount of time that is been exposed to that differential.

Since the level and the amount of time are the key factors in determining the temperature level that the product will reach, we will describe the danger of heat damage by three aspects: first, the level of temperature to which the wine has been exposed; second, the amount of time that the wine has been exposed to a certain temperature and finally, the cumulative effect of the level and length of exposure. The level of exposure to extreme temperature can be represented by the percentage of shipments that recorded at least one reading above a certain temperature threshold. The length of exposure can be quantified by the amount of time the wine was exposed at or higher temperature level.

To quantify the cumulative danger we will use a variation of the proposed quality degradation function by Rong et al. [96]. The authors propose that the rate of quality degradation Dq can be correlated to the Arrhenius equation, which relates the temperature to the speed of the chemical reactions. To determine the cumulative degradation to which the wine is subjected during transport, we will use as a proxy the sum the increment in the speed of chemical reactions $Dq(t, T_b)$ that occurs along the complete transport process. For the different factors that are involved in the equation, the pre-exponential factor k_0 and the activation energy E_a constants, we will use the values determined by Converti et al. [33] for starch hydrolysate alcohol fermentation by Saccharomyces cerevisiae which corresponds to the yeast used in wine fermentation.

The Arrhenius equation relates the speed of the chemical reactions to temperature, hence for any given temperature level we can determine the speed at which the reactions are taking place. Since we are interested in determining the effect of transport temperatures in the quality of the wine, we will contrast the speed of chemical reactions that would have occurred under controlled storage conditions with the ones that concurred under transport conditions.

The concept of comparing quality degradation from a baseline was also used by Ferrer et al. [46] and Tisjkens and Polderdijk [105]. In the first paper the authors quantify the degradation in the quality of wine grapes as the harvest deviates from the optimal date. In the second they use the Arrhenius equation to determine a reaction rate, which is defined as the coefficient between the reaction at a reference level and at a absolute temperature level. As a baseline (T_b) we will use the value given by the chemical reaction speed function that would be obtained by keeping the wine at a optimal temperature of 13 °C, so this value will correspond to the speed of the chemical reactions that would occur at optimal storage conditions of the wine. The choice of 13 °C is because it represents the optimal temperature for aging a wine in a cellar [22]. We will also use other base lines (20 °C, 30 °C and 35 °C) because it allows to determine the average percentage increase in the speed of chemical reactions at different levels or thresholds.

$$\triangle\, Dq(t,T) = k_0 t \cdot e^{-E_a/RT} - k_0 t \cdot e^{-E_a/RT_b} \tag{1}$$

By determining the differential speed in the chemical reactions, between the optimal storage conditions and the values obtained with the transport temperatures in Function 1, we can quantify the net effect that the temperature had on the wine. If we take this differential and divide it by the optimal storage conditions chemical reaction speed, we can obtain the increase (as a percentage) in the chemical reactions due to the exposure to temperatures during transport. Finally, if we integrate this value for all the length of the trip, we can obtain the cumulative increment in the chemical reactions due to the exposure to temperatures above the level. This value is obtained by integrating Function 2. In Figure 3 we can observe that at 25 °C the rate of the chemical reactions have been increased on 100%.

$$
\begin{aligned}
\% \triangle Dq(t,T) &= \frac{k_0 t \cdot e^{-E_a/RT} - k_0 t \cdot e^{-E_a/RT_b}}{k_0 t \cdot e^{(-E_a/RT_b)}} \\
\% \triangle Dq(t,T) &= e^{(-E_a/R)(1/T - 1/T_b)} - 1 \qquad (2)
\end{aligned}
$$

The level of temperature is not the only risk factor that can affect the product. Daily variability in temperature can also present a danger, since wine as any liquid expands and contracts under temperature changes. Boulton [19] indicates that thermal expansion of wine between 20 °C and 40 °C is 0.8% of the volume, so for a regular 750 ml bottle of wine there will be a 0.3 ml change in volume for each degree Celsius. This expansion and contraction of the liquid can cause the cork to move like a piston, drawing air into the bottle and then expelling it, so that the wine may be at risk of oxidation. Consequently there is a concern over the variation in bottle pressure given by the thermal expansion and contraction and secondary effects of increased vapor pressure and diminished carbon dioxide solubility associated with such cycles. To the best of our knowledge, no study has analyzed the temperature differential required to move the cork. To capture the temperature variability danger, we will determine the daily temperature range given by the maximum and minimum temperature.

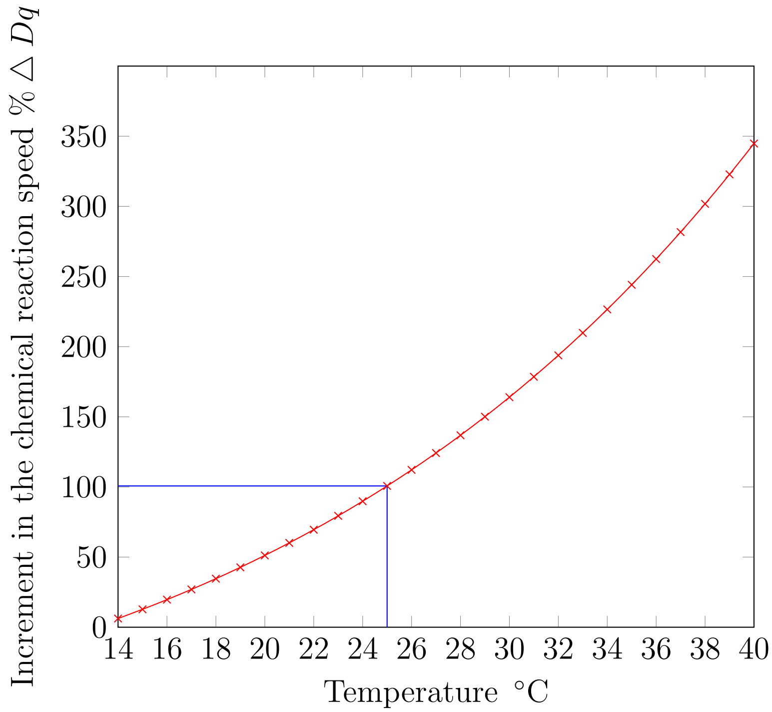


Figure 3: Percentage of increment in the speed of chemical reactions at a 13 °C base line at different temperature levels.

2.5 Wine shipment temperature tracking

We have documented the temperature of international shipments of wine for over 4 year period. The tracking process starts at the winery (in either Argentina, Australia, Chile or South Africa) where they attach a pre-stamped envelope, which has a temperature recording device. The envelope is eventually recovered by the importer, distributor, retailer or customer and is mailed back to us. Once the envelope has arrived to us, we download the temperature information and relate it to the tracking information of the container. Each shipping company publishes a different level of detail of container tracking information, nevertheless all of them publish the time and location in which the container was either loaded or unloaded from a vessel. This information, along with the time and place in which the shipment was instrumented and retrieved, allows us to obtain the location and determine the season in which the event took place. In this way we can correlate for each time and temperature data point, the position (northern or southern hemisphere and location) and phase of transport. In appendix A.1 there is a detailed explanation of the process.

We have recovered over one thousand temperature recording devices from the wine producing countries (see Table 1) and a total number of 481,233 readings of date, time and temperature have been collected. Using information from the website of the shipping companies we were also also able tell approximately where the container was at all times. For 735 out of 1007 of the retrieved devices we have the complete position tracking history. In total 269 different routes were fully tracked (Figure 4).

Table 1: Devices recovered by country of origin.

Country Origin	**Number**	**Percentage**
Argentina	64	6.4%
Australia	244	24.2%
Chile	659	65.4%
South Africa	25	2.5%
USA	15	1.5%
Total	**1007**	**100%**

Between the years 2008 and 2012 we recovered the temperature information of 735 shipments of wine (Table 2). We indicate shipments and not devices, because a shipment or container may have more than one device placed inside. This is done to capture the temperature in different locations inside the container and determine if there are differences. Of those shipments, we have been able to determine the geographical position of the container for each phase, by tracking the position of the vessel, in 517 or 70.3% of the shipments.

Our data includes multiple routes between ports. For example, we have tracked 5 different routes that containers followed from Melbourne to Oakland. Routes vary not only by the path they take, but also in the number and location of transshipment points. The reason for such variability is that freight forwarders generally use the least-cost route to move the containers [35].

Table 2: Shipments tracked by country of origin.

Country Origin	Number	Percentage
Argentina	32	4.4%
Australia	152	20.7%
Chile	515	70.0%
South Africa	23	3.1%
USA	13	1.8%
Total	**735**	**100%**

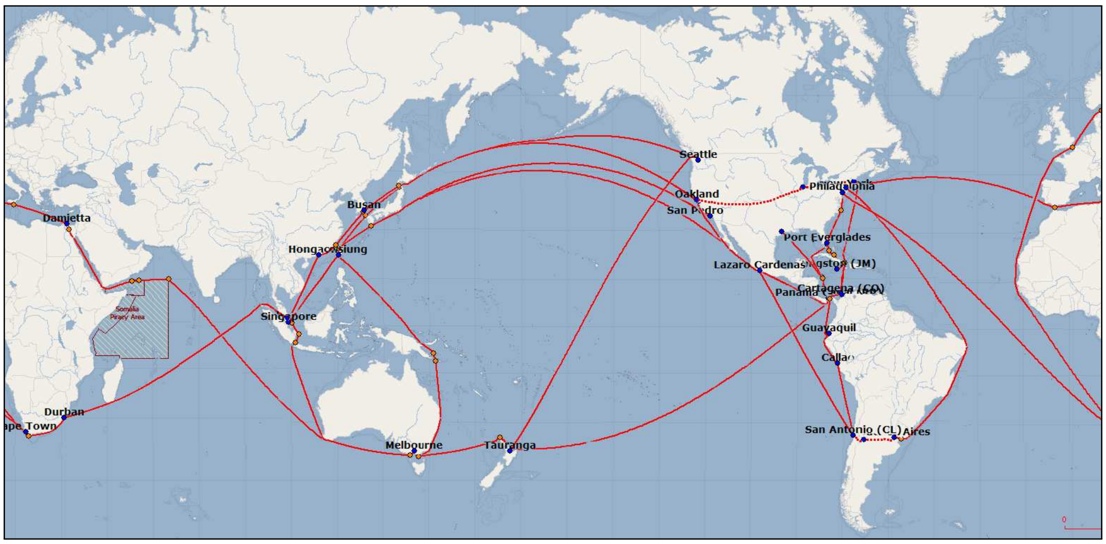


Figure 4: Map of tracked routes.

Most of the shipments we tracked come from Chile and Australia (Table 2) to the US. Accordingly we have chosen to focus our analysis on the information coming from those origins.

2.5.1 Temperatures during transport

Table 3 shows summary statistics of the shipments coming from Australia and Chile. The mean temperature of 20.28 °C with a maximum of 67 °C and a minimum of −10 °C. The mean and median are outside the ideal range of 13 − 15 °C red wine [19]. This suggests that the product might be at danger. Worryingly, over 25% of the observations are above 25 °C which suggests the possibility of heat damage. The lower 25% of the observations (lower quartile) minimum is at 16°C, which suggests a minimal danger for low temperature exposure. If we look at the minimum temperature, of $-9.5°C$, we can observe that shipments have been exposed to unsuitable low temperatures.

Table 3: Shipment temperature descriptive statistics.

Statistic	°C
Max	67.00
Mean	20.50
Median	20.50
Min	-9.50
Std Dev	6.19
Upper Quartile	28.50
Lower Quartile	16.00
N	**429,357 Obs.**

Figure 5 shows the percentage of temperature readings above a certain temperature threshold. 55.7% of the readings were above 20 °C, which can be considered worrisome; 27% were above 25 °C, which is considered dangerous and 6.7% of the readings were above 30 °C, which can likely damage the wine.

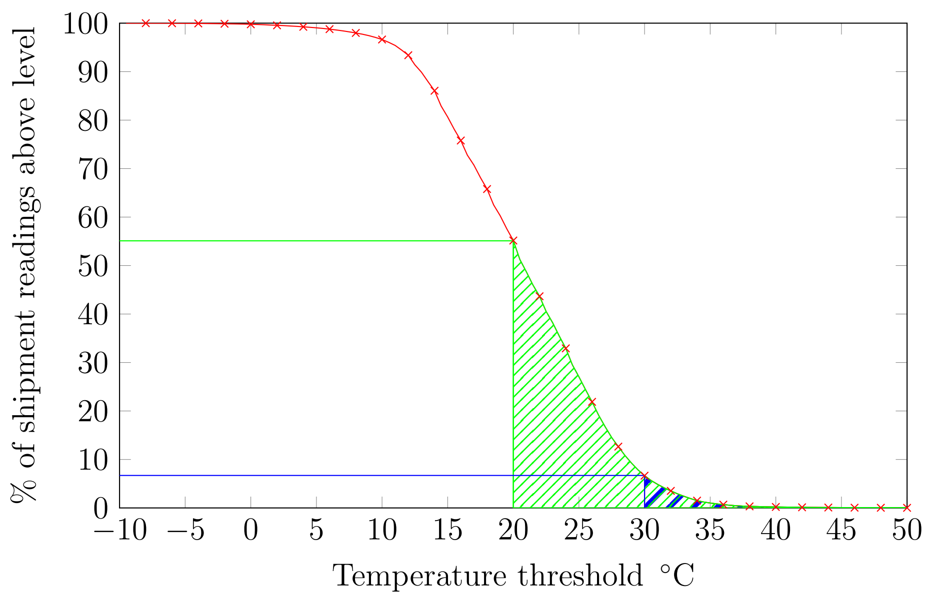
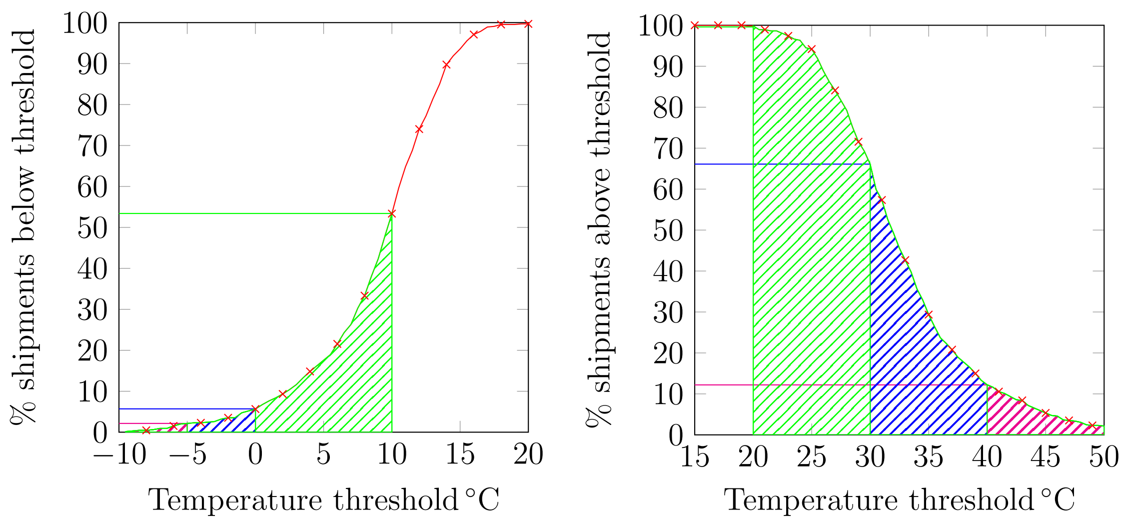


Figure 5: Percentage of readings above temperature threshold.

Analyzing the danger by the percentage of readings above a threshold, does not fully represent the potential damage to the product due to extreme temperature exposure during transport. To more accurately quantify the possibility of exposure to unsuitable temperatures, we need to examine the percentage of shipments, and not just readings, that were exposed to temperatures above a given threshold. Figure 6 presents the results of the percentage of *shipments* with at least one reading above a certain temperature threshold. Results indicate that over 99.6% of the shipments reported at least one temperature reading over 20 °C, 66% of the reported shipments had at least one reading over 30 °C and 12.2% of the shipments presented at least one reading over 40 °C. These results clearly indicate an elevated danger of the wine being exposed to high temperature during the transport.

In Figure 6a we look exposure to lower temperatures and observe that 53.5% of the shipments recorded at least one reading below 10 °C and 5.7% of the shipments recorded at least one reading below 0 °C. These results suggest that there is a danger of low temperatures, but it is much less than the danger of high temperatures.

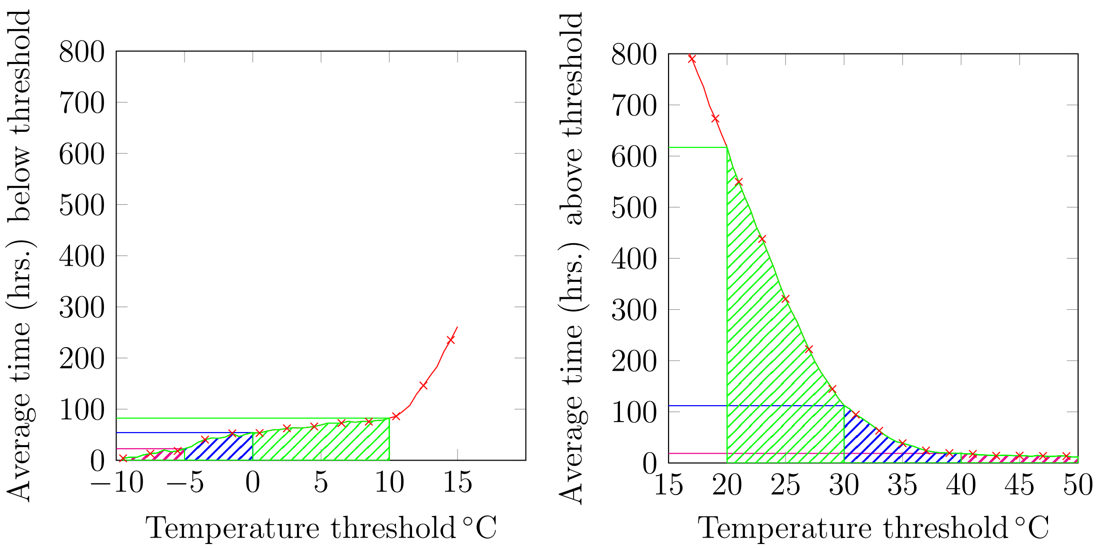


(a) Below threshold

(b) Above threshold

Figure 6: Percentage of shipments that recorded temperatures (a) below or (b) above threshold.

The intensity of the danger of high temperature, measured by average time of exposure, can be observed in Figure 7b. Results suggest that on average a shipment of wine is exposed for 617 hours to temperatures above 20 °C, for 112 hours above 30 °C and for 19 hours above 40 °C.



(a) Below threshold

(b) Above threshold

Figure 7: Average time (Hrs.) that the shipments are (a)above or (b)below threshold.

The intensity of the danger regarding low temperature exposure can be observed in Figure 7a. A shipment of wine is exposed on average for 82.5 hours to temperatures below 10 °C, for 54.3 hours to 0 °C or below and for 22.7 hrs to −5 °C or below. Even though low temperatures are not likely (only 2.1% of shipments reported temperatures below −5 °C), once presented, the duration of the exposure to those levels can be significant.

2.5.2 Temperature variability.

To quantify the temperature variability, for each shipment and for every day we have computed the temperature range (maximum temperature minus minimum temperature). This allows us to quantify the variability in the daily extreme temperatures to which the wine has been exposed. Table 4 shows the descriptive statistics for the daily temperature ranges. The wine shipped from Australia or Chile to the US is exposed to a mean daily range of 3.15 °C and with a standard deviation of 4.27 °C. If we look more closely into the quartiles, we can observe that 50% of the observations are between 0.5-4.0 °C.

Table 4: Daily temperature range descriptive statistics.

Statistic	°C
Max	42.40
Mean	3.19
Median	1.50
Min	0.00
Std Dev	4.26
Upper quartile	4.00
Lower quartile	0.50
Number obs.	**26,615 obs.**

Figure 8 shows the histogram of the daily temperatures ranges. The frequency rapidly decreases as the range increases, with only 6.8% of the reading daily ranges above 10 °C.

Figure 9 shows the percentage of shipments with at least one daily temperature variation above a certain threshold. At least 54.7%, 42.9%, 30.4% and 14.1% of the devices had at least one, two, four and eight daily temperature range readings above 10 °C, respectively. These results indicate that temperature variability is indeed a concern during transport, since 8.3% of the shipments were at some point exposed to a daily temperature range of at least 25 °C. This range can induce an expansion of 1% in the volume of the liquid inside the bottle [19] which can result in oxygen intake or cork movement or in the worst case, cork displacement.

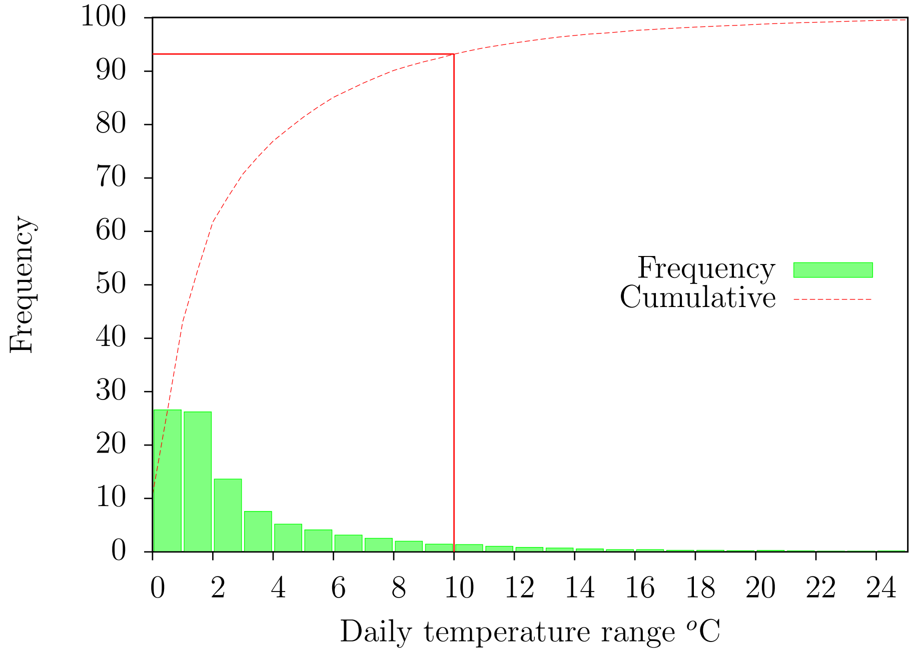


Figure 8: Daily temperature range histogram.

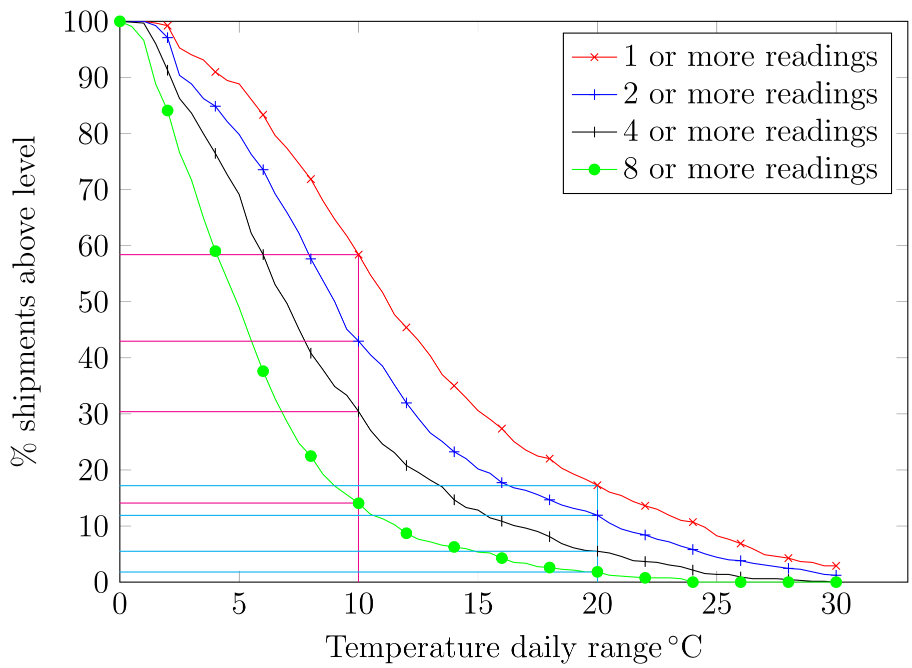


Figure 9: Percentage of devices that recorded more than one, two, four or eight daily temperature ranges readings above threshold.

2.5.3 Cumulative heat transfer and its effect on the cumulative chemical reactions

The cumulative effect of temperature is reflected in an increment in the speed of the chemical reactions of the wine given by $\% \triangle Dq$, can be observed in Table 5 and Figure 10. At the baseline of 13 °C, which corresponds to the storage/shipping of the wine at optimal conditions, we can observe that the cumulative chemical reactions in the wine have been significantly increased, with an average increase in the speed of 76.2% compared to the optimal storage condition. If we look at the upper quartile, at least one fourth of the shipments increased the speed of the chemical reactions by 94.7% or more.

Table 5: Statistics for percentage of increase in the chemical reactions ($\% \triangle Dq$) for 13 °C, 20 °C, 30 °C and 35 °C base line.

Statistic	$\% \triangle Dq$ at 13 °C	$\% \triangle Dq$ at 20 °C	$\% \triangle Dq$ at 30 °C	$\% \triangle Dq$ at 35 °C
Max	162.8 %	100.2 %	248.9 %	142.2 %
Mean	76.2 %	37.1 %	13.0 %	5.4 %
Median	75.6 %	35.7 %	6.1 %	0 %
Min	0 %	0 %	0%	0 %
Std Dev	26.8 %	16.6 %	22.8 %	13.2 %
Upper quartile	94.7 %	47.9 %	17.4 %	0 %
Lower quartile	58.4 %	25.1 %	0 %	0 %
Number obs.	660	660	660	660

As we increase the base line, the increment in reaction speed is exponentially reduced (Figure 10). At the 20 °C base line level, which is at the upper threshold of the storage temperatures of red wine, the average speed is at 37.1% and 25% of the shipments have a cumulative percentage increase in the chemical reactions of 47.9% or more.

In general we can observe that shipping temperatures have significantly increased the cumulative chemical reactions of the wines. If we consider that accelerated chemical reactions are negative to the quality of the product, temperature plays significant

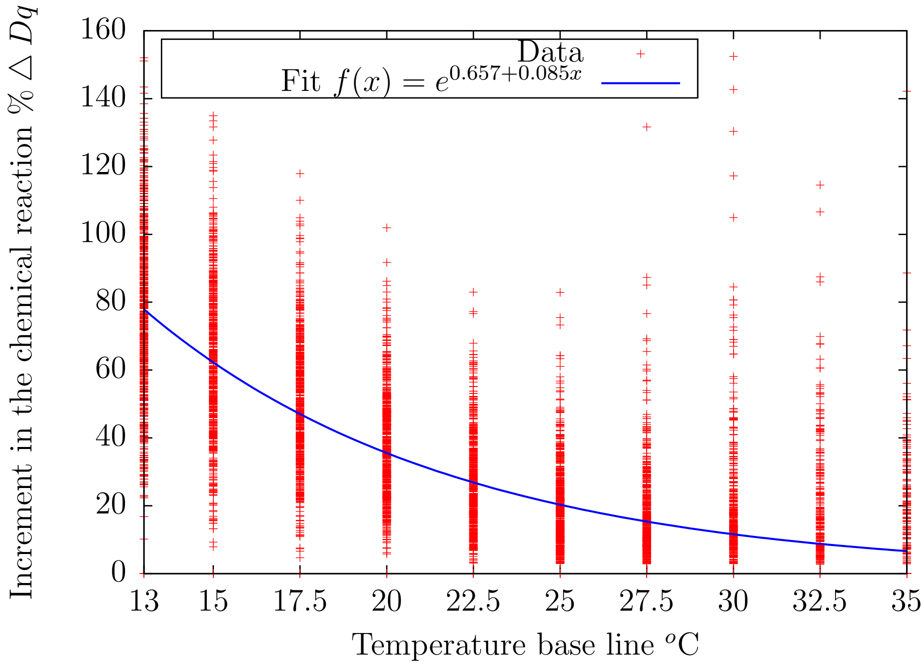


Figure 10: Percentage of cumulative increase in the chemical reactions (% △ Dq) for 13 °C, 15 °C, 17.5 °C, 20 °C, 22.5 °C, 25 °C, 27.5 °C, 30 °C,32.5 °C and 35 °C base line.

factor in the reduction of the quality of the product. Having wines that have increased their cumulative chemical reactions in 76.2% in average and quarter of the shipments have an increment of 94% or more in the reaction speed.

2.5.4 Differences in the temperature according to season and phase of transport

An important factor that influences the temperatures to which the shipments will be exposed during their transport is the season of the year (summer/winter). To note the effect of seasons we divide the calendar year into 2 seasons: June-September and December-March. Table 6 shows the seasonal distribution of the shipments that we were able to fully track, coming from Australia and Chile to the US.

Figure 11 shows that there is no significant difference in the extreme temperature danger, measured as the percentage of shipments with one or more readings above threshold, for the Dec-Mar and June-Sept shipments from Chile to the US.

Table 6: Number of shipments by season and country of origin.

Country	**June-Sept**	**Dec-March**
Australia	31	0
Chile	77	108
Total	**108**	**108**

The similarity can also be observed in the time that the shipments were exposed to temperatures above 30 °C (Figure 12). One explanation for the similarity between extreme temperature danger of the Dec-March and June-Sept periods is that shipment is always exposed to a summer season but in a different hemisphere (southern hemisphere on Dec-March and Northern hemisphere during June-Sept). If we observe below the 30 °C the difference in the exposure time at a temperature level between periods is significant, with the average time exposure in the June-Sept period significantly above the Dec-March period. This can be explained because during the summer of the Mediterranean weather, high temperature (above 30 °C), are only present in reduced periods of time during the day and nights in general are cool. If we compare this condition with the summer in South of the US, were high daily temperatures during the summer can extend for long periods of time and even through the night, this explains the significant difference in exposure below 30 °C.

Figure 13 shows the percentage of cumulative increase in the chemical reactions for the 13 °C, 20 °C, 30 °C and 35 °C base line for Dec-March and June-Sept periods. Looking at the fit lines we can determine that on average for the June-Sept periods the cumulative increment in chemical reactions is higher than for the Dec-March periods. So the reaction speed for the wines transported in the northern hemisphere summer is higher than the reaction speed that occurs in the wines transported in the winter of the same hemisphere at a significance level of 95%. We can notice that, as was the case for the time exposed, as the threshold is closer to 30 °C, the gap is reduced. So as the temperature threshold is over 30 °C the cumulative chemical reactions for

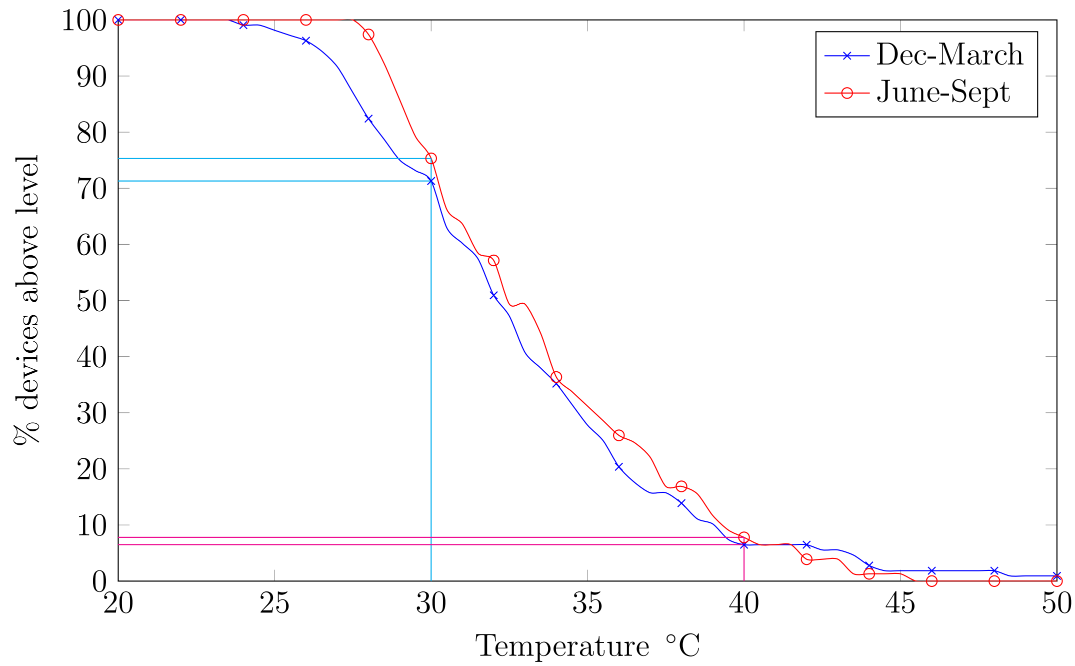


Figure 11: Percentage of shipments from Chile to the US with one or more readings above threshold by season.

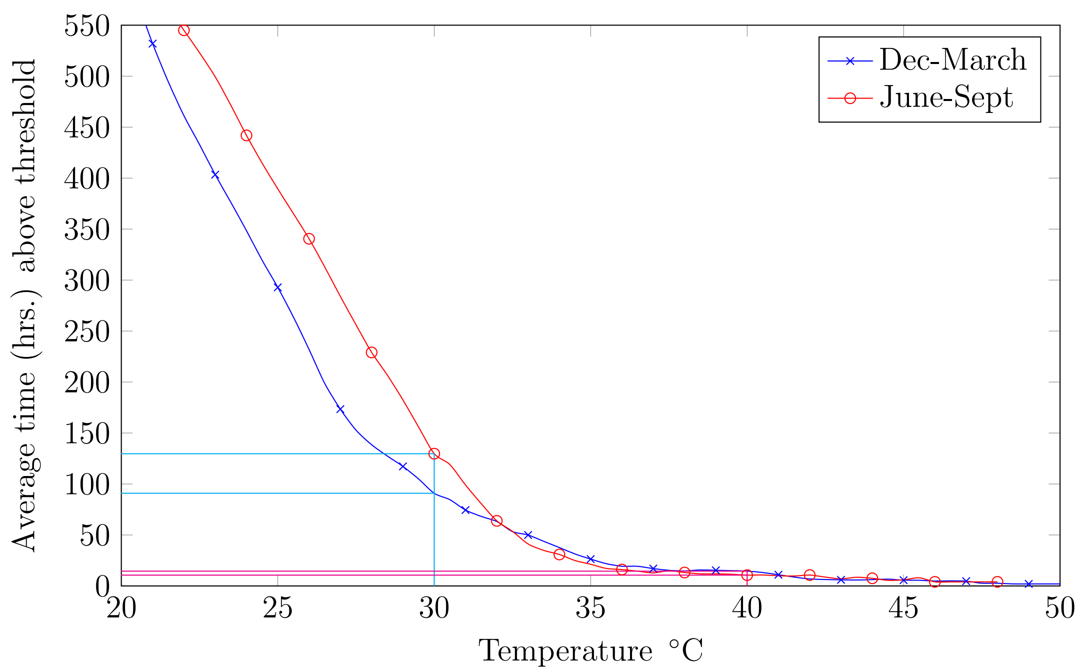


Figure 12: Average shipment time (hrs.) exposure above a given temperature threshold from Chile by season.

both periods are similar.

The explanation to the seasonal temperature exposure and cumulative chemical reactions, for a temperature threshold of over 30 °C, being similar for both periods, is the fact that the container is always exposed to a summer season in one of the hemispheres. This phenomenon is clearly observed in Figure 14 where on one side we can see that the danger of extreme temperature exposure is higher for the Dec-March periods for the winery-to-port and transshipment phases. On the other side, if we look at the at-sea and the destination port to importer phase for the June-Sept periods, the danger is greater than the Dec-March periods.

At the winery-to-port phase (Figure 14a) the danger is much smaller compared to the other stages. This situation is explained by the Mediterranean weather predominant in the wine producing countries. As an example in Chile, mean maximum temperatures in the summer do not exceed 33 °C, while in the winter they barely go over 20 °C. The combination of relative mild weather plus nearness to ports translates in less heat and sun exposure for the shipment. We can observe seasonal differences in the average time exposed to high temperatures, but the magnitude of it is not significant to indicate a danger for the product (Figure 15a).

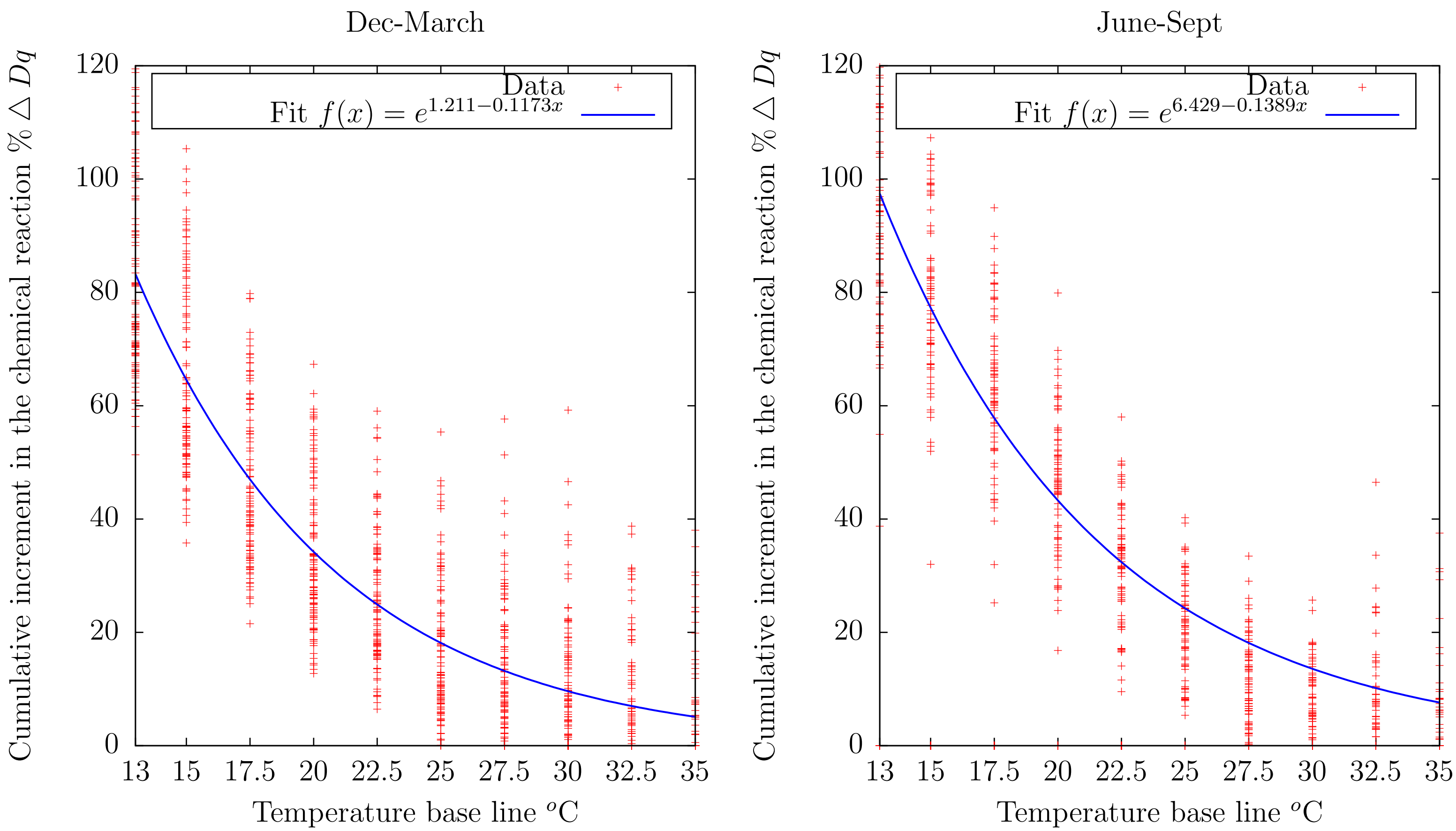


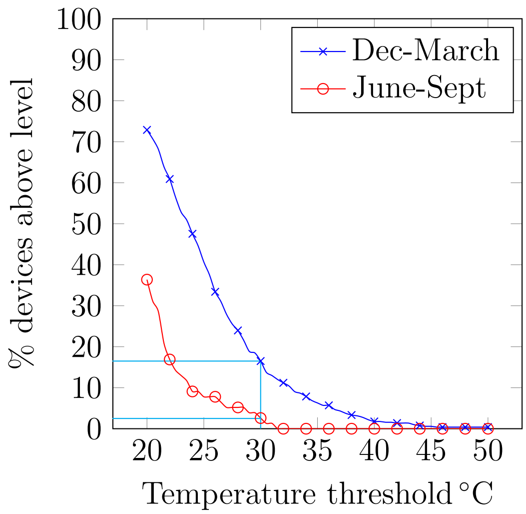
Figure 13: Percentage of cumulative increase in the chemical reactions (% $\triangle$ Dq) for 13 °C, 15 °C, 17.5 °C, 20 °C, 22.5 °C, 25 °C, 27.5 °C, 30 °C,32.5 °C and 35 °C base line for the Dec-March and June-Sept periods.

During the at-sea phase (Figure 14b) temperatures above 30 °C occur during both the Dec-March and June-Sept periods. The extreme temperature exposure generally occurs near the equator in January, where the nighttime mean surface temperature of the sea can exceed 30 °C, while in July these extreme temperatures move from the Equator to the Gulf of Mexico. There is no difference between the average time spent at or above a threshold for the seasons and a typical container is exposed to temperatures above 30 °C for 96 Hrs. (Figure 15b).

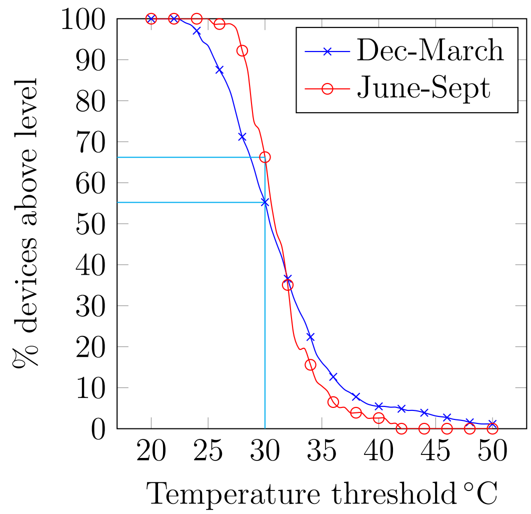
The extreme temperatures are mostly found at the transshipment phase. We observe both a high occurrence of extreme temperature and exposure for both seasons (Figures 14c and 15c). This can be explained because most of the transshipment ports are located near the equator, where temperatures do not vary much from season and are generally high.

At the end of the supply-chain, from the port-of-destination-to-the-importer or distributor phase (Figure 14d), we can observe the highest danger of extreme temperature exposure during June-Sept, with 71% and 9.2% of the shipments exposed to temperatures above 30 °C and 40 °C, respectively. On the other side, during Dec-March, only 41% and 6% of the shipments were exposed to temperatures above 30 °C and 40 °C. The difference between the seasons in the level of exposure is also significant (Figure 15d). The elevated danger, during June-Sept, can be explained by the high temperatures in the United States in the East coast and the interior during the summer.

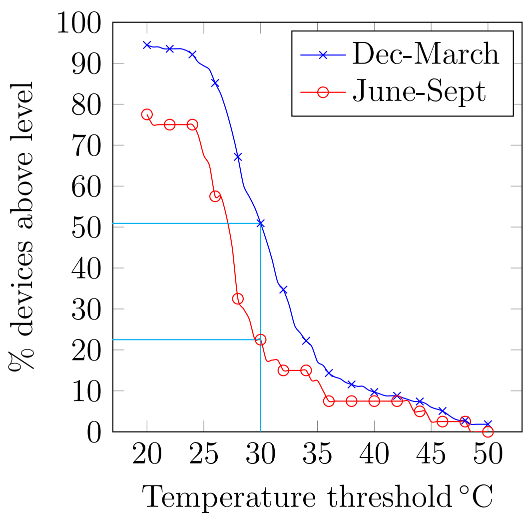
Table 7 shows the mean grouping for percentage increase in chemicla reaction speed ($\%\triangle Dq$) for the 13 °C base line by transport phase during Dec-March and June-Sept. The transshipment during Dec-March and the destination-port-to-importer or distributor phase during June-Sept are the phases and periods of highest cumulative danger. The least danger is in the transport from the winery-to-port phase during the June-Sept. From Figures 16, 17, 18 and 19 we can observe that the cumulative danger



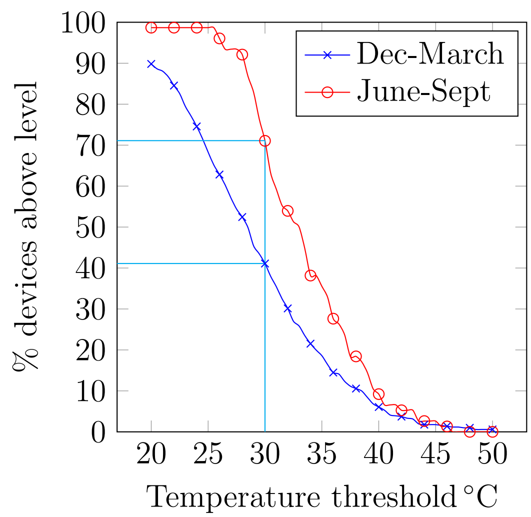
(a) From the winery to the port.



(b) At Sea.

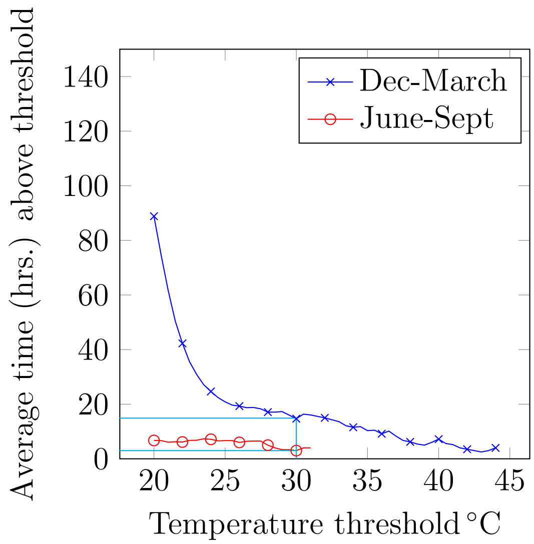


(c) Transshipment.

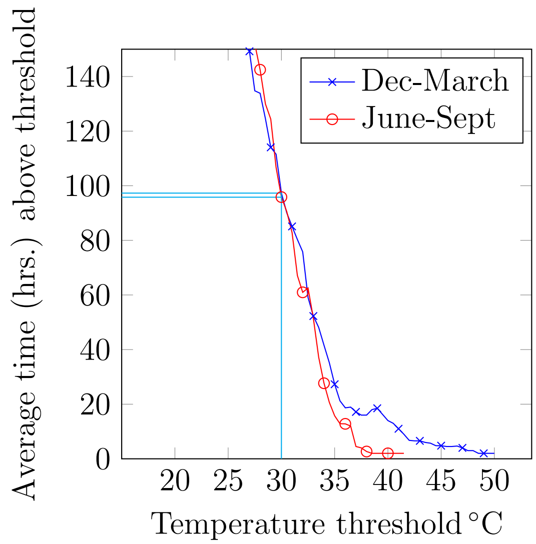


(d) Destination port to importer.

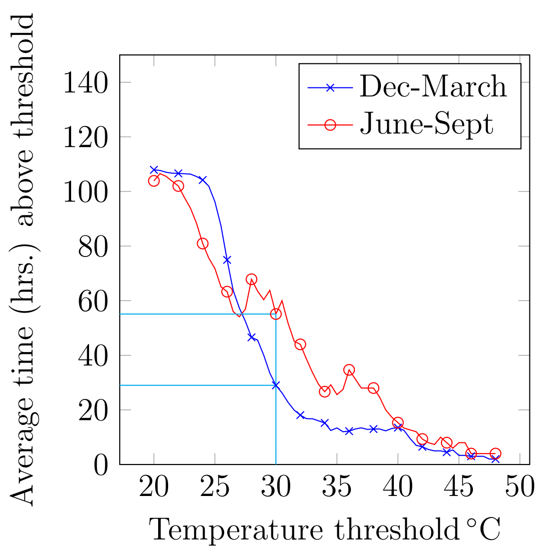
Figure 14: Percentage of shipments from Chile to the US that recorded one or more temperatures above threshold by season and phase of transport.



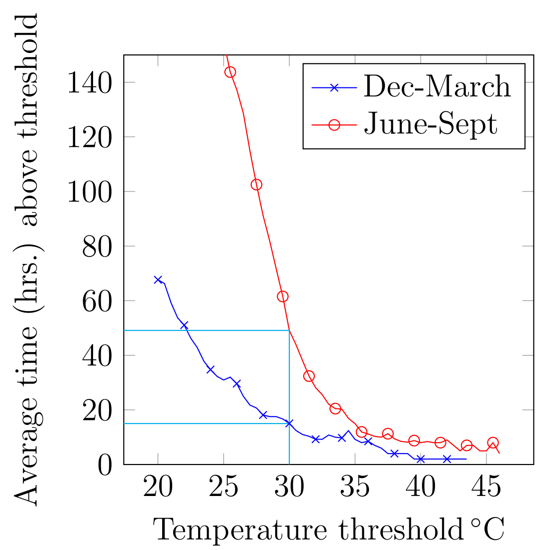
(a) From the winery to the port.



(b) At Sea.



(c) Transshipment.



(d) Destination port to importer.

Figure 15: Average time (hrs.) spent above threshold by season and phase of transport.

is exponentially reduced as we relax the standard. For the 13 °C base line we can observe significant differences between the different seasons, with average percentage of cumulative increase in the chemical reactions of above 100% for the transshipment phase in Dec-March, destination port to importer in June-Sept and the at-sea phase during both periods. For the above 30 °C base line there are no significant differences between seasons in the cumulative danger for all phases.

Table 7: Mean grouping for percentage of cumulative increase in the chemical reactions ($\% \triangle Dq$) for 13 °C base line by transport phase and Dec-March and June-Sept periods.

Period / Transport Phase	Mean $\% \triangle Dq$ at 13 °C
Dec-March / Transshipment	130.6%
June-Sept / Dest. Port to import.	123.2%
Dec-March / At sea	97.3%
June-Sept / At sea	90.0%
June-Sept/ Transshipment	89.2%
Dec-March / Winery to port	57.2%
Dec-March / Dest. Port to import.	51.2%
June-Sept / Winery to port	21.7%

Temperature variability is significant for the winery-to-port and destination-port-to-importer phases during Dec-March, with over 50% of the device having at least one daily temperature range above 10 °C (Figure 20). The at-sea and transshipment phases do not present much daily variability because, the container is generally surrounded by other units that serve as insulation. And because the transshipment ports are located near the Equator, where daily temperature variability are not very significant.

We can draw the following conclusions for the shipments from Chile to the US. First, the destination-port-to-importer during the June-Sept period is the phase that presents the highest danger for the product, because even though it does not present the highest danger of the extreme temperatures or length of exposure, it has the

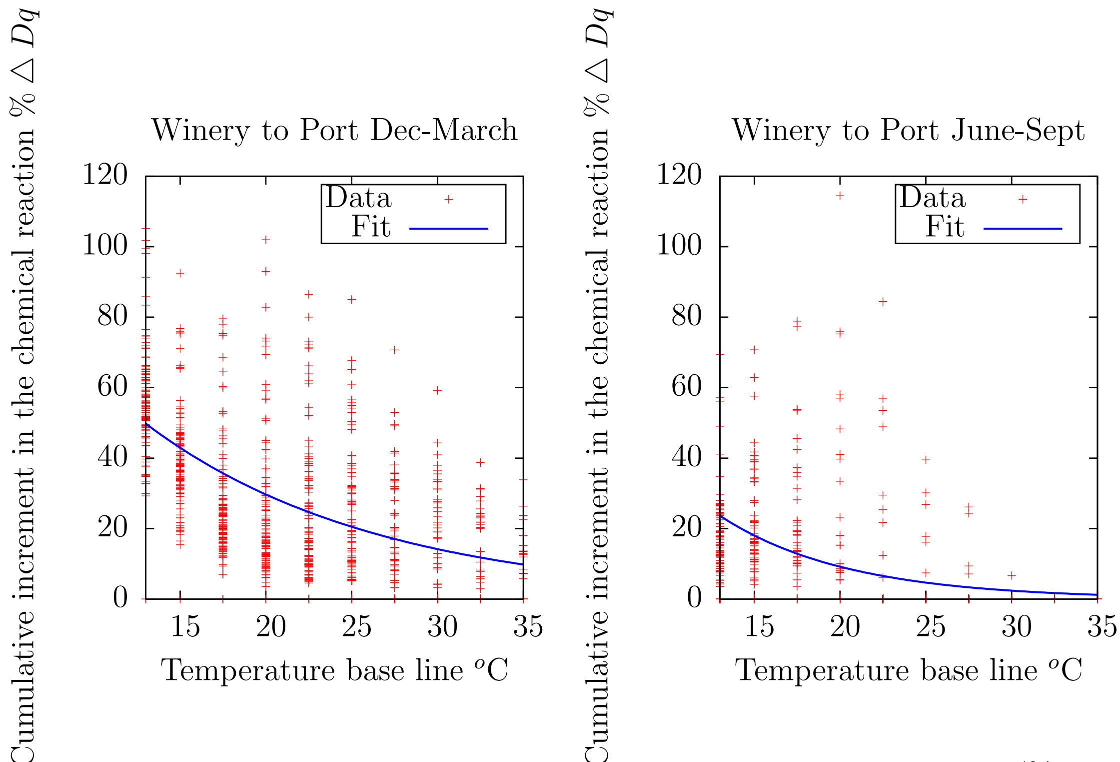


Figure 16: Percentage of cumulative increase in the chemical reactions (% $\triangle$ Dq) at winery to port phase for 13 °C, 15 °C, 17.5 °C, 20 °C, 22.5 °C, 25 °C, 27.5 °C, 30 °C,32.5 °C and 35 °C base line for the Dec-March and June-Sept periods.

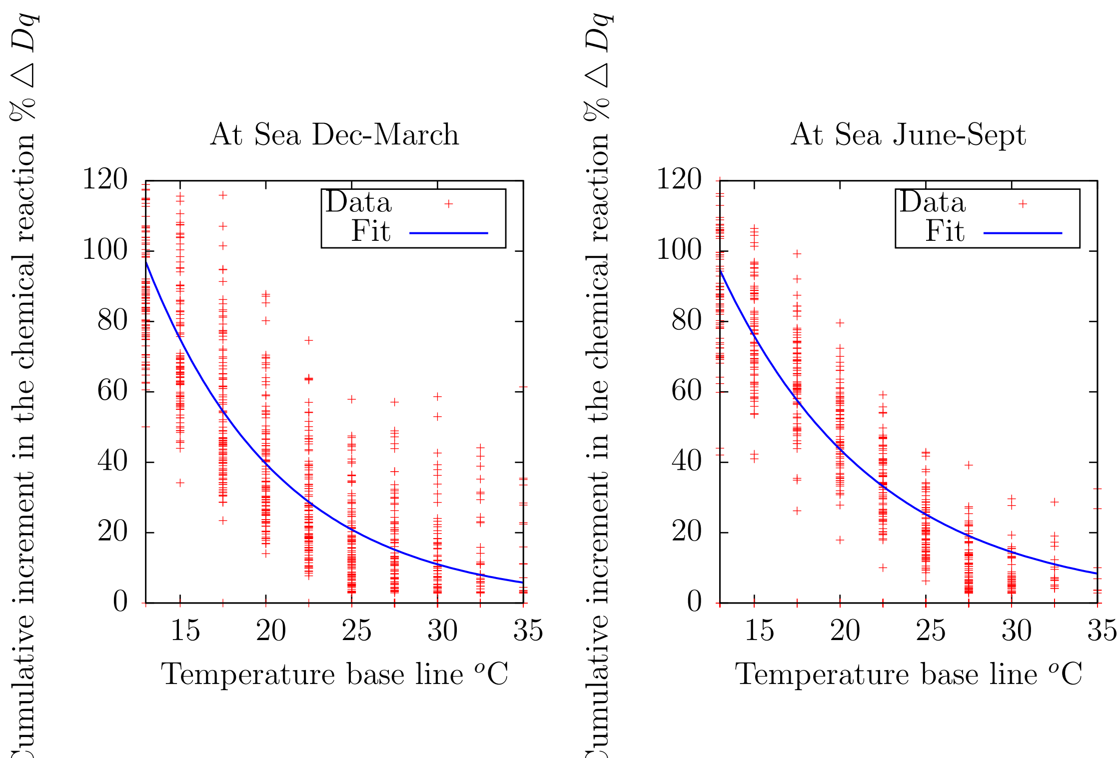


Figure 17: Percentage of cumulative increase in the chemical reactions (% $\triangle$ Dq) at sea phase for 13 °C, 15 °C, 17.5 °C, 20 °C, 22.5 °C, 25 °C, 27.5 °C, 30 °C,32.5 °C and 35 °C base line for the Dec-March and June-Sept period s.

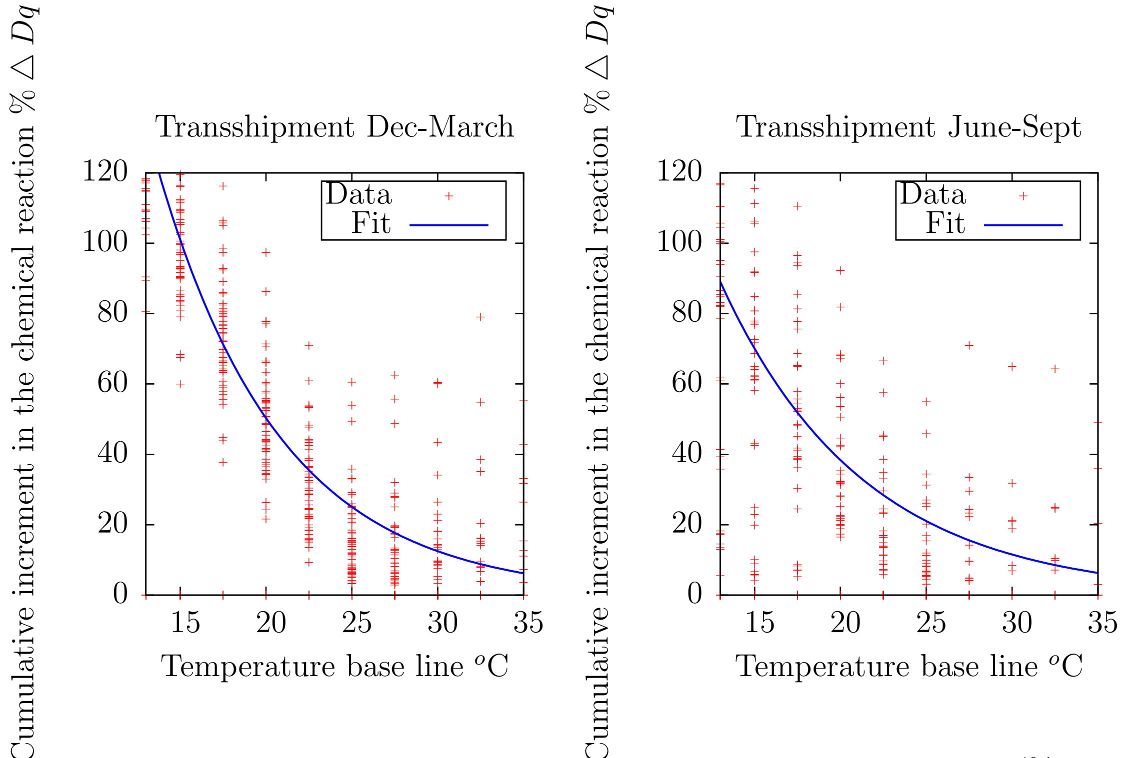


Figure 18: Percentage of cumulative increase in the chemical reactions (% △ Dq) at transshipment phase for 13 °C, 15 °C, 17.5 °C, 20 °C, 22.5 °C, 25 °C, 27.5 °C, 30 °C,32.5 °C and 35 °C base line for the Dec-March and June-Sept periods.

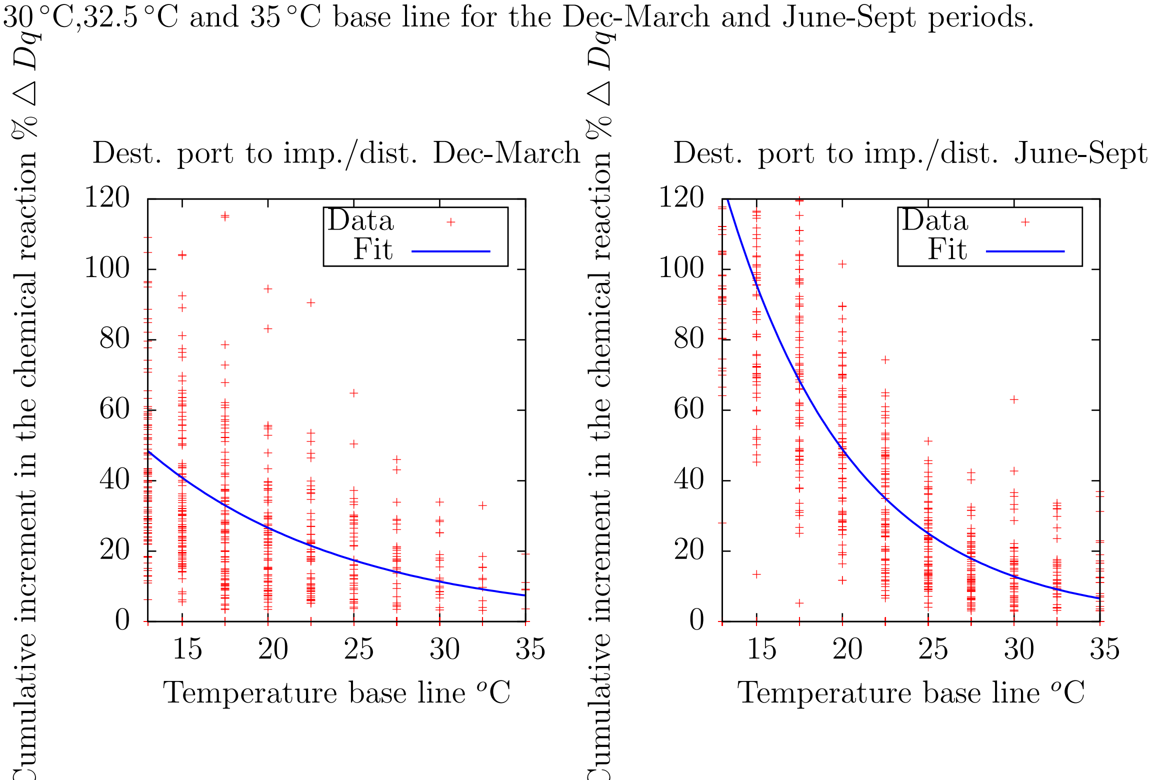
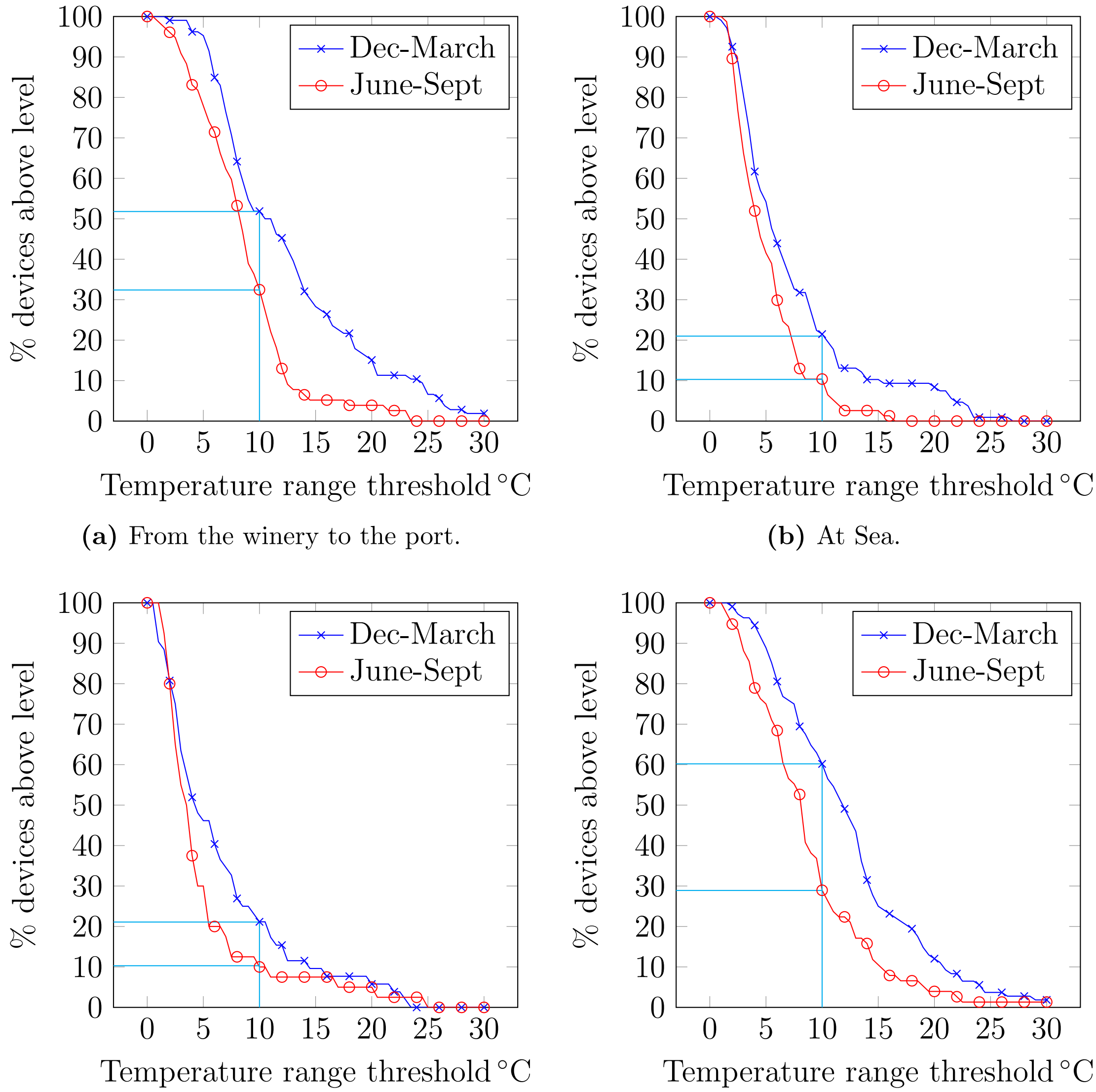


Figure 19: Percentage of cumulative increase in the chemical reactions (% △ Dq) at destination port to importer/distributor phase for 13 °C, 15 °C, 17.5 °C, 20 °C, 22.5 °C, 25 °C, 27.5 °C, 30 °C,32.5 °C and 35 °C base line for the Dec-March and June-Sept periods.



(a) From the winery to the port.

(b) At Sea.

(c) Transshipment.

(d) Destination port to importer.

Figure 20: Percentage of shipments from Chile to the US that recorded one or more daily temperatures ranges above threshold by season and phase of transport.

highest cumulative effect with an average cumulative chemical reaction increase of 130%. The next most dangerous phase is the at-sea, independent of the season, due to to high temperatures at one of the hemispheres and at the Equator. Also this phase takes the longest of all four, leaving more time for the shipment to be exposed to extreme temperatures. The transshipment phase on both periods comes in third place, because this phase happens in ports located near the Equator, which have high temperatures, and also because the container is left in the stack without any protection from direct sunlight. Finally, the winery-to-port phase in winter has a lowest exposure to extreme temperatures. Nevertheless, it cannot be completely ruled out as a danger-less phase, since the temperature ranges (max - min temperatures) are comparatively high with respect to the other phases.

2.5.5 Detailed analysis for transport phase and route

As shown previously on Figure 4, routes from a given country of origin to a destination can vary in many ways. First, they can vary on the choice of port of origin. For example wineries in Mendoza, Argentina can send their shipments through the Chilean ports of Valparaiso or San Antonio on the Pacific coast, or they can ship through a port in Argentina, such as Mar del Plata on the Atlantic coast. Also the Australian wineries use the ports of Adelaide or Melbourne. The choice of port of origin is important because the container needs to be transported from the winery to the port by either truck or rail, leaving the cargo directly exposed to the elements and also to the dangers of extreme temperatures. For example, for a container leaving from Mendoza to the port of San Antonio, the distance is 303 miles, for the same container leaving from the port of Mar del Plata, the distance traveled is more than double, with 726 miles, almost doubling the amount of time of transport and the danger of exposure to extreme temperatures. The choice of route can also vary because the freight forwarder can select a route with or without transshipment and also in which port the transshipment is performed. Finally, its possible to select the port of arrival to the US and also the mode of transportation from the port to its final destination (truck, train or a combination). According to conversations with people from the industry, the main driver that governs these choices is cost. The objective of the freight forwarder is to find the minimum cost route from an origin to a destination, with small consideration on the potential danger of extreme temperature exposure for the cargo.

To determine if there is any effect of the choices over the danger of extreme temperature exposure, we will now look in detail at the transport phases that previously we determined as the ones with the greatest temperature danger. First, we will look at the transshipment phase and compare the temperatures at the different transshipment ports to determine the comparative danger of extreme temperature. The next critical phase is the destination-port-to-importer/distributor phase. Here we will analyze the temperature profiles according to the port of entry to the US and also according to its destination. Finally we will look at the at-sea phase, analyzing whether the choice of destination port has any effect on extreme temperature danger.

2.5.5.1 Transshipment points

The transshipment phase was determined as the phase in which the largest percentage of cumulative increase in the chemical reactions happens. To determine if there are differences in the extreme temperature dangers, we will look at the different ports of transshipment. Table 8 summarizes the number of devices and at which port the container was transshipped.

We compared the readings independent of the time of year, since most of the transshipment ports through which we tracked the wine are located near the equator, where temperatures do not vary significantly over the year. Table 9 summarizes the temperatures within shipments during transshipment.

Table 8: Number of shipments by destination coast and port of transshipment.

Transshipment port	# Ship. West Coast	# Ship. East Coast	Percentage
Balboa (PA)	20	111	60.1%
Cartagena (CO)	1	37	17.5%
Manzanillo (PA)	5	16	9.6%
Lazaro Cardenas (MX)	13	0	6.0%
Callao (PE)	0	9	4.1%
Freeport (BH)	0	4	1.8%
Kingston (BH)	0	2	0.9%
Total	39	179	100.0%

Table 9: Temperature summary statistics by port of transshipment.

Transshipment port	N	Max	Mean	Median	Min	Std. Dev.	Up quart.	Low quart.
Balboa (PA	7906	48.00	25.90	26.00	16.00	3.00	27.50	24.50
Callao (PE)	312	19.50	15.34	15.50	11.50	1.83	16.50	14.00
Cartagena (CO)	1812	44.00	26.72	26.50	17.50	2.46	28.25	25.50
Freeport (BH)	216	32.00	27.13	27.00	25.00	1.53	28.00	26.00
Kingston (BH)	144	32.50	27.74	27.50	23.50	2.12	29.00	26.50
L. Cardenas (MX)	936	46.50	28.35	28.00	20.59	3.95	30.00	25.60
Manzanillo (PA)	1128	32.00	25.50	25.50	20.00	2.63	27.50	24.00

To have depth on our analysis we will use the information of those ports in which we have been able to track 5 or more shipments. In Figure 22, 23 and Table 10 we can observe that Lazaro Cardenas is the port with the highest percentage of shipments with temperatures above threshold, highest average exposure time and finally with the highest cumulative percentage increase of chemical reactions. The port of Cartagena has a similar behavior, belonging to the same group of cumulative chemical reaction at a threshold of 13 °C. The Cartagena port has a smaller standard deviation in the cumulative increase of chemical reaction, compared with Lazaro Cardenas, because the temperatures are also less variable than Lazaro Cardenas. The ports located in Panama in the cumulative danger appears in second place, with a mean cumulative increase in their chemical reactions of 118.9%, forming a different group which indicates that these ports have less cumulative danger than Lazaro Cardenas and Cartagena. Nevertheless, if we observe the percentage of shipments above threshold, the ports of Panama present a higher percentage of shipments above 35 °C than the port of Cartagena. This leads us to conclude that even though the ports of Panama have a lower cumulative danger, since they have a higher danger of exposure, their overall danger should be similar to the ports of Lazaro Cardenas and Cartagena. The port of Callao presents the lowest danger of extreme temperature exposure for all measurements, due to its location at a significant distance from the equator.

Table 10: Mean grouping for transshipment ports by percentage of cumulative increase in the chemical reactions ($\% \triangle Dq$) at 13 °C base line. Lines indicate different groups.

Port	Mean $\% \triangle Dq$ at 13 °C	Std. Deviation $\% \triangle Dq$ at 13 °C
Lazaro Cardenas (MX)	131.9 %	34.0 %
Cartagena (CO)	131.0 %	25.1 %
Balboa & Manzanillo (PA)	118.9 %	31.9 %
Callao (PE)	19.6 %	11.4 %

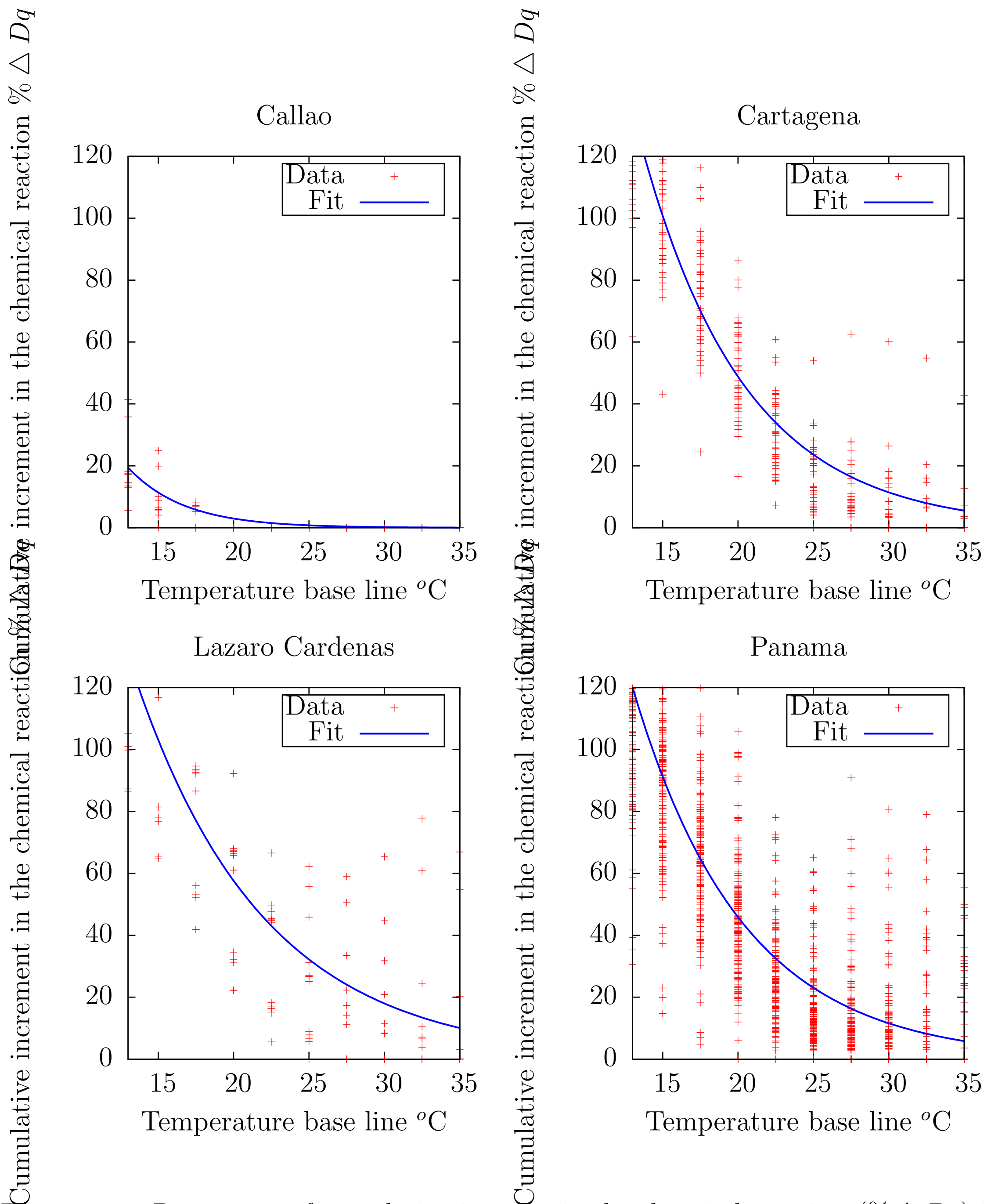


Figure 21: Percentage of cumulative increase in the chemical reactions(% $\triangle Dq$) for 13 °C, 15 °C, 17.5 °C, 20 °C, 22.5 °C, 25 °C, 27.5 °C, 30 °C,32.5 °C and 35 °C base line for different transshipment ports.

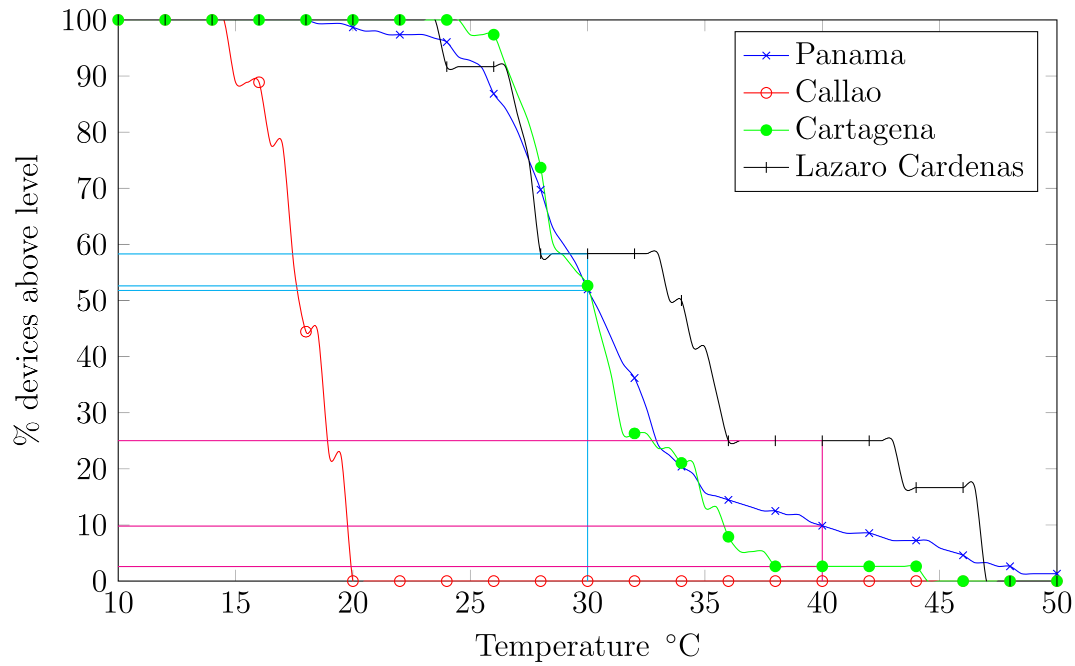


Figure 22: Percentage of shipments to the US with one or more readings above threshold by transshipment port.

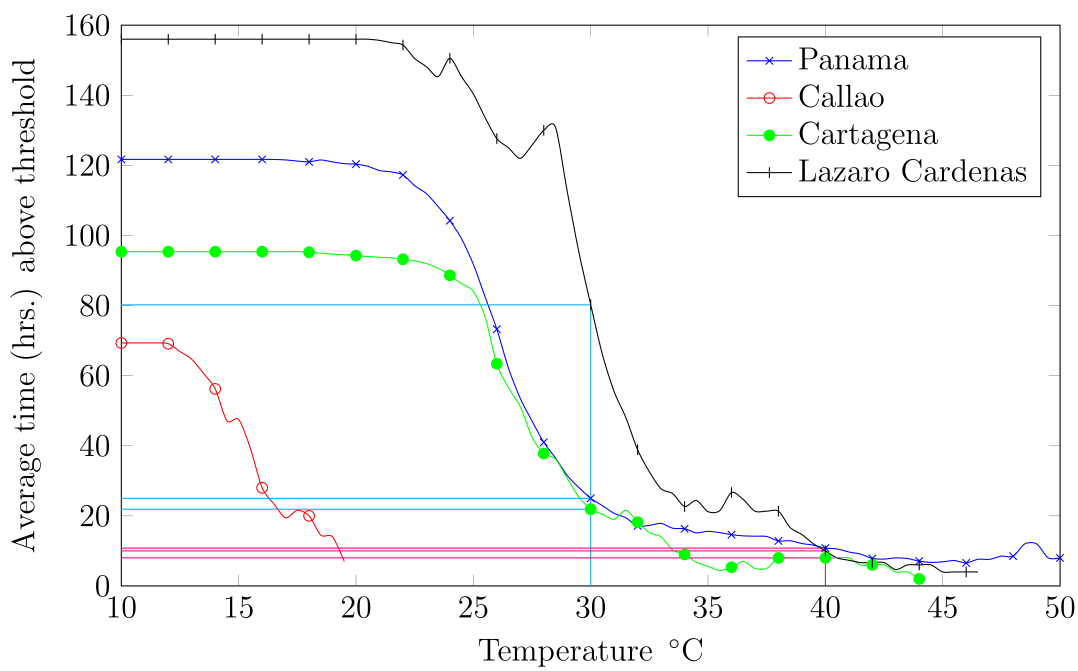


Figure 23: Average shipment time (hrs.) above threshold at transshipment phase by port.

2.5.5.2 Port to importer/distributor

The next phase that has the highest temperature danger for the wine is the port to importer/distributor phase. To analyze the dangers we will look at the different routes that the product takes within the US, from the ports of entry to the destination of the product. The objective is to determine if there exists any patterns in the dangers of extreme temperature exposure within the routes taken.

We have recovered information of shipments entering the US in 13 different ports destined to one of the 38 states within the US. We will group the data according to their port and destination. We will define 3 different locations areas for the ports: West, Northeast and Southeast. The West ports correspond to all located on the west coast of the US. For the Northeast, all of the ports on the east coast to the north and including the Philadelphia port. Finally, for the Southeast all of the ports in the east coast and south of Philadelphia. To aggregate the destination information we will define 4 regions: West, Midwest, Northeast and South; according to how close they are to a port area. The distribution of the different destinations within the US can be observed in Table 11.

Previously we determined that the season (winter/summer) had a significant effect on the temperature to which the shipments were subjected during this phase. Table 12 shows the total number of shipments that we have tracked by periods according to destination port area and region of destination. We have a significant number of shipments for both periods for the shipments arrived to: the Northeast ports destined to the Northeast of the US, Southeast ports to the Midwest, Southeast ports to the South and finally, West ports destined to the West of the US. The concentration of the shipments in those ports and destinations is because the choice of entry port is generally driven by proximity to the final destination in order to minimize transportation costs.

Figures 24 and 25 show the percentage of shipments to the US with one or more

Table 11: Number of shipments by destination and census region.

State	Region	# Ship.	State	Region	# Ship.
Alabama	South	9	New Hampshire	Northeast	5
Arizona	West	6	New Jersey	Northeast	19
Arkansas	South	6	New Mexico	West	3
California	West	37	New York	Northeast	102
Connecticut	Northeast	30	North Carolina	South	17
Delaware	South	8	Ohio	Midwest	8
Florida	South	50	Oregon	West	5
Georgia	South	32	Pennsylvania	Northeast	15
Idaho	West	1	Rhode Island	Northeast	7
Illinois	Midwest	11	South Carolina	South	1
Iowa	Midwest	2	Tennessee	South	6
Kansas	Midwest	1	Texas	South	5
Louisiana	South	4	Vermont	Northeast	10
Maine	Northeast	5	Virginia	South	1
Maryland	South	12	Washington	West	8
Massachusetts	Northeast	20	Washington DC	South	2
Michigan	Midwest	9	West Virginia	South	1
Minesota	Midwest	5	Wisconsin	Midwest	11
Missouri	Northeast	6	**Total**		**480**

Table 12: Total number of shipments and by period according to destination port area and Importer/Distributor region.

Dest. port area	Imp./Distributor region	Total # shipments	Jun–Sept	Dec–Mar
Northeast	Midwest	15	4	7
Northeast	Northeast	210	65	68
Northeast	South	10	1	4
Southeast	Midwest	36	10	16
Southeast	Northeast	2	1	0
Southeast	South	150	41	64
Southeast	West	1	0	1
West	West	56	31	17
	Total	480	153	177

readings above threshold by port area and census region destination during June–Sept and Dec–March, respectively. The Southeast port to South region is the route with the highest extreme temperature danger, with the number one ranking in the percentage of shipments above threshold for both periods. It presents long exposure to high temperatures in the summer months and with a percentage of cumulative increase in the chemical reactions of 149.8% and 54.9% for the June-March and Dec-March periods, respectively (Tables 13 and 14). The elevated danger is present at both seasons is due to the fact that the southern region is more exposed to extreme temperatures in both seasons, than the other regions. This is reflected in the multiple reports of cork displacement along this route. There have been a smaller number of such reports from the shipments arriving to the Northeast ports destined to the Northeast region and none from shipments arriving to the West coast bound to the west region.

The Northeast port to Midwest region route also has high temperature danger, specially during June–Sept, with a high percentage of cumulative increase in their chemical reactions of 107.3%. If we look at the variability it also has the highest value of all routes, indicating that the cumulative increase in the chemical reactions of shipments made during this period and route cannot be assured.

On the other side, the West ports to the West region route is the one with the lowest occurrence, intensity and cumulative danger for both periods. This is because all of the shipments are destined to California, which has mild weather in both seasons.

Figure 26 shows that the Southeast ports to the Midwest region have longest mean exposure to extreme temperatures but it is not the one with the highest percentage of devices above threshold. The lower exposure events but extended times is due to the distance that the container needs to travel to reach its final destination and so it leaves more time to be exposed to the climatic conditions. For the West ports to West region route, because the Importers/Distributors are mostly located near the

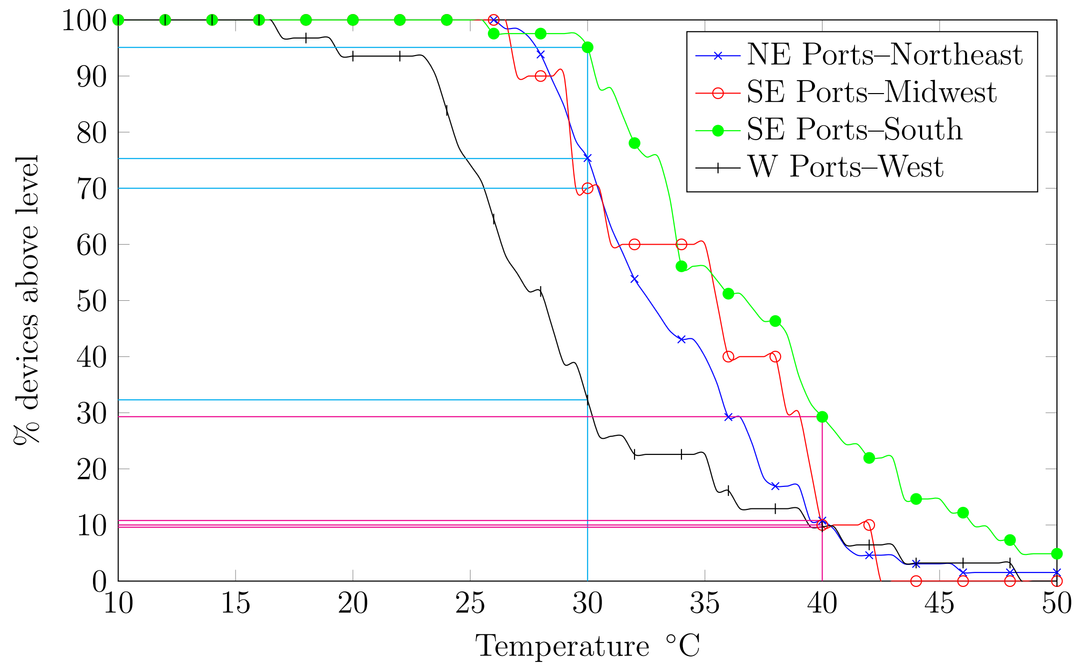


Figure 24: Percentage of shipments to the US with one or more readings above threshold during June-Sept period by port area and census region destination.

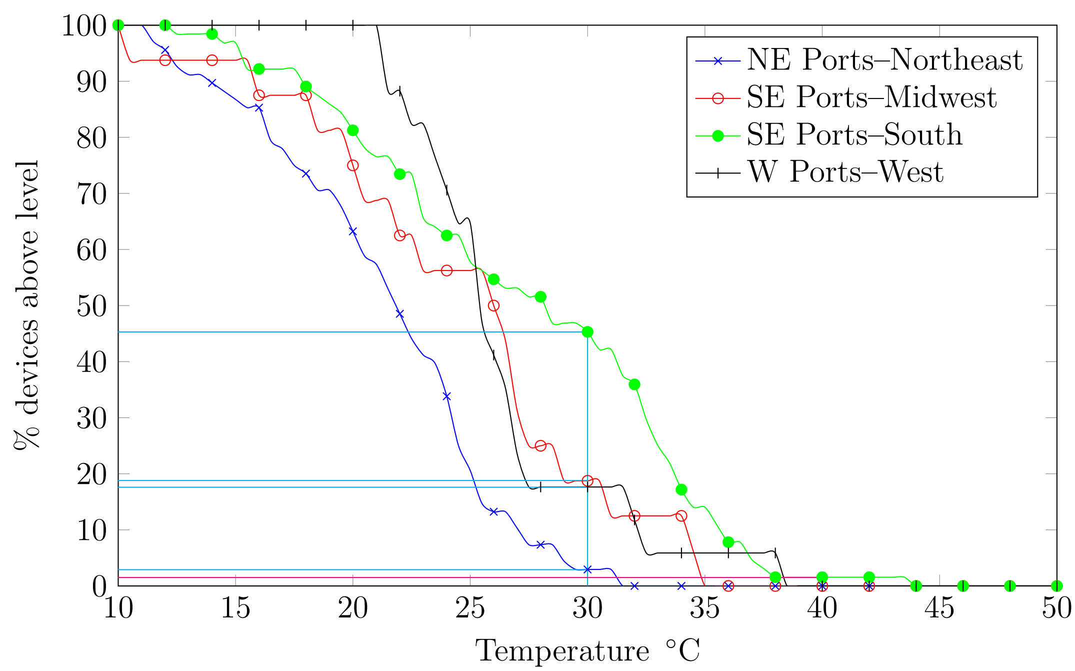


Figure 25: Percentage of shipments to the US with one or more readings above threshold during Dec-March period by port area and census region destination.

ports, the container takes less time to reach its destination. So even for the June-Sept period the length of exposure is not very significant. The same situation happens for the Northeast ports to the Northeast region shipments.

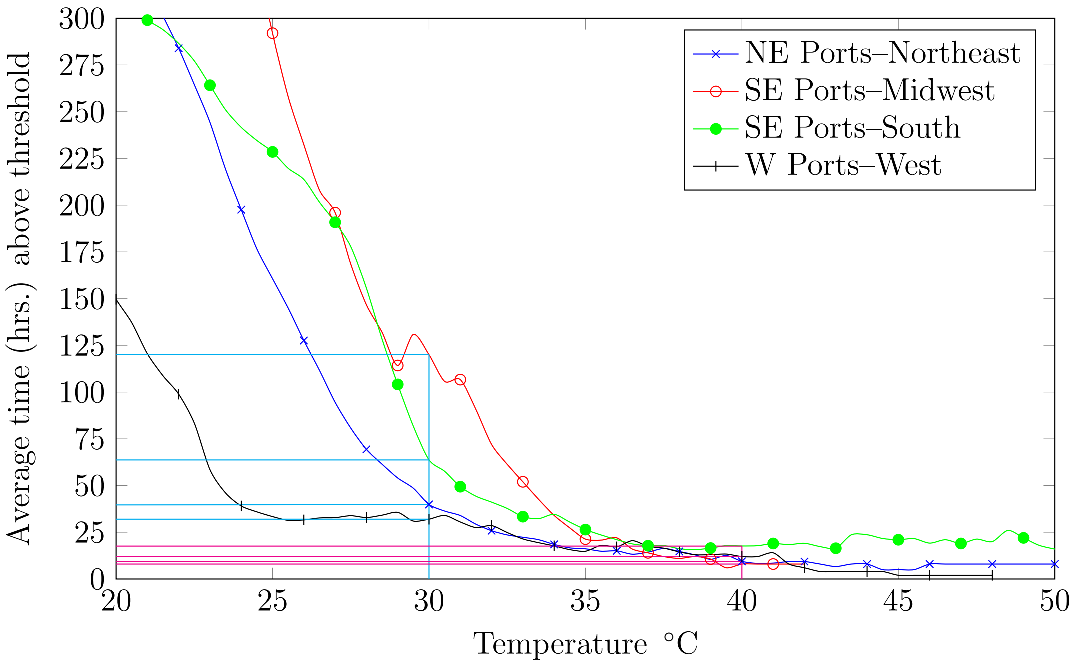


Figure 26: Average shipment time (hrs.) above threshold during June-Sept period by port area and census region destination.

Table 13: Mean grouping of percentage of cumulative increase in the chemical reactions (% $\triangle$ Dq) at 13 °C base line for June-Sept period for port of destination to importer/distributor phase. Lines indicate different groups.

Port-Destination	Mean % $\triangle$ Dq at 13 °C	Std. Deviation % $\triangle$ Dq at 13 °C
SE Ports-South	149.8 %	5.3 %
NE Ports-Midwest	115.2 %	17.2 %
SE-Midwest	110.7 %	10.9 %
NE-Northeast	108.0 %	4.3 %
W-West	60.4 %	6.8 %

2.5.5.3 At sea

During the at-sea phase is where the wine spends most of its transport time and also is the one that comes second in the danger of extreme temperature exposure

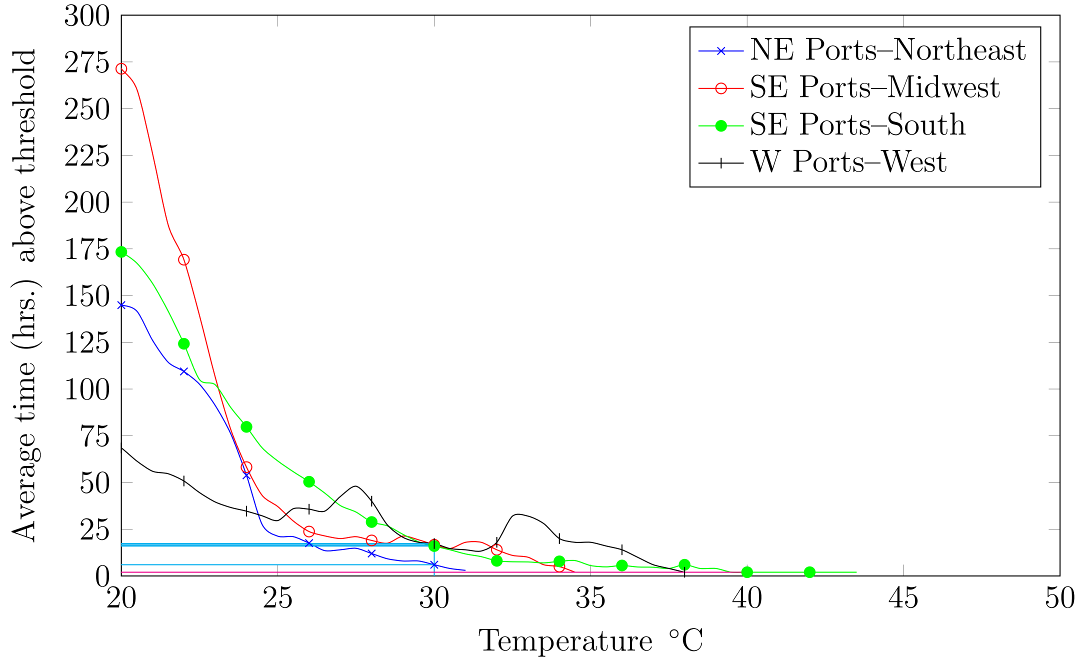


Figure 27: Average shipment time (hrs.) above threshold during Dec-March period by port area and census region destination.

Table 14: Mean grouping of percentage of cumulative increase in the chemical reactions (% $\triangle$ Dq) at 13 °C base line for Dec-March period for port of destination to importer/distributor phase. Lines indicate different groups.

Port-Destination	Mean % $\triangle$ Dq at 13 °C	Std. Deviation % $\triangle$ Dq at 13 °C
NE Ports-Midwest	107.3 %	18.0 %
SE Ports-South	54.9 %	5.9 %
W-West	48.6 %	11.5 %
SE-Midwest	37.2 %	11.9 %
NE-Northeast	34.6 %	5.7 %

and intensity, after the transshipment. We will analyze and determine if there are any temperature patterns in the shipping routes that can be exploited to reduce the dangers. To analyze how the choice of shipping route and specifically the port of destination affect the danger of exposure to extreme temperatures, we have aggregated the ports by location. We have defined 3 different locations areas for the ports: West, Northeast and Southeast. The West ports correspond to all located on the west coast of the US. For the Northeast, all of the ports on the east coast to the north and including the Philadelphia port. Finally, for the Southeast all of the ports in the east coast and south of Philadelphia. Table 15 shows the number of shipments by port of destination and area.

We have information on 480 shipments coming from Chile to 13 different entry ports to the US (Table 15). We have aggregated the temperature information of all of the ports in the West coast of the United States because they have similar temperatures due to the Pacific current. In the case of the ports located in the East coast of the United States, we can observe a larger differences in the north/south temperature profiles because of the effects of the Atlantic and Gulf current.

Table 15: Number of shipments from Chile by destination port.

Port	Area	No Shipments	Percentage
Los Angeles	West	22	4.6%
Oakland	West	7	1.5%
Seattle	West	10	2.1%
Boston	Northeast	3	0.6%
Newark - New York	Northeast	226	47.1%
Philadelphia	Northeast	15	3.1%
Norfolk	Southeast	6	1.3%
Baltimore	Southeast	45	9.4%
Charleston	Southeast	66	13.8%
Houston	Southeast	10	2.1%
New Orleans	Southeast	10	2.1%
Port Everglades	Southeast	60	12.5%
Total		480	100.0%

The routes from Chile to the Northeast ports present the highest danger of extreme temperature. This route has the highest percentage of shipments above threshold, average time and the highest cumulative increase in the chemical reactions ($\% \triangle Dq$) at 13 °C base line. There are two reason behind the elevated danger: the first, is the fact that this route is the longest one from the other two, which leaves the cargo exposed for more time to the climatic conditions. The second reason is that, as the southeast route, it passes through the Panama Canal and the Gulf of Mexico where temperatures in the summer can easily be above 30 °C.

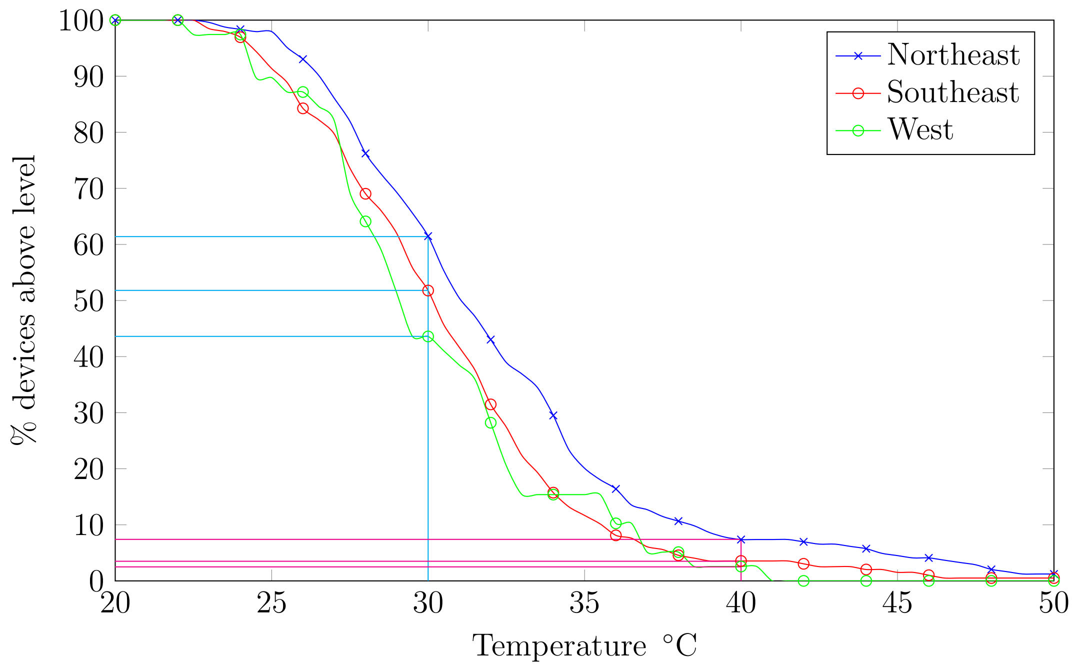


Figure 28: Percentage of shipments from Chile to the US with one or more readings above threshold at sea phase.

In the case of the West route, the occurrence of an extreme temperature event is smaller because there is a buffering effect of the Pacific current, which produces coolers nights, so the intensity of the event is much smaller compared to the ones on the Southeast or Northeast coasts.

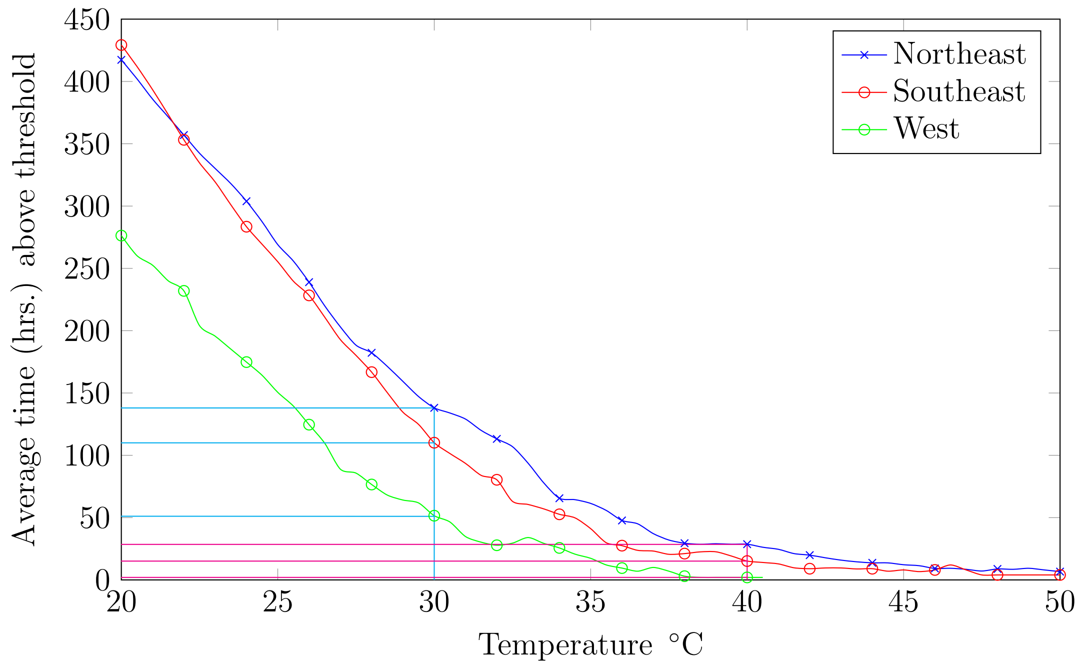


Figure 29: Average shipment time (hrs.) above threshold at sea phase from Chile.

Table 16: Mean grouping of percentage of cumulative increase in the chemical reactions (% $\triangle$ Dq) at 13 °C base line for at sea phase by area of destination. Lines indicate different groups.

Area of destination	Mean % $\triangle$ Dq at 13 °C	Std. Deviation % $\triangle$ Dq at 13 °C
North East	97.8 %	1.81 %
South East	85.0 %	2.0 %
West	84.4 %	4.5 %

2.6 General discussion and implication for shipping

To our knowledge we have the largest database of temperature information from international shipments of wine to different destinations within the United States, specially from Australia and Chile. This has allowed us to determine the danger of extreme temperature exposure in terms of: level and occurrence of the event, amount of time of exposure and the cumulative effect. We have also been able to relate the dangers with the season and the phase of transport in which they happen. With all the above information we are able to make specific recommendations for the shipment of wine from the southern hemisphere to the US. The recommendations are:

1. **Avoid transshipment:** If possible avoid this phase because it has the largest dangers in level, intensity and cumulative effect. If it is not possible to avoid this phase, it is recommended that the time that the container spends at this phase should be minimized (fast transshipment) or the process be done in a port not located near the Equator (eg. Callao).

2. **Fast movement of shipments within the US during the June-Sept period:** The time spent in the destination port to importer/distributor in the June-Sept phase should be minimized to avoid extreme temperature exposure. Special care must be taken for the shipments arriving to the South east ports bound to the South and Midwest area and the ones arriving to the Northeast ports to the Northeast and Midwest areas, because they present the highest percentage of cumulative increase in the chemical reactions.

3. **Shipping during the Northern hemisphere winter (Dec-March):** there is smaller danger of extreme temperature exposure for the shipments done during the Dec-March than for the ones during the June-Sept, so its preferable to ship the wines during the winter of the Northern hemisphere to reduce the

danger of heat exposure. Shipping the wine only during the Northern hemisphere winter is a practice currently being used by many French wineries to avoid exposure to extreme temperatures.

CHAPTER III

EFFECT OF THERMAL LINERS OVER CONTAINER TEMPERATURES.

3.1 Introduction

The temperature inside a container is mostly determined by the heat transfer with the environment through conduction. A way to reduce the danger of exposure to extreme temperatures is bt decreasing the conduction of heat between the environment and the inside of the container. This can be achieved by using a thermal liner that physically covers the entire internal wall of the container, acting as an insulating barrier for the cargo from the external temperatures. Figure 30 shows a liner installed in a container ready to be loaded with cargo.

Figure 30: Temperature liner installed in a container.

The liner protects the cargo from the temperature damage by reducing the thermal conductivity. The reduction on the thermal conductivity is reflected in two ways: first, by insulating the inside of the container from extreme outside temperatures and second, by lowering the daily temperature variation through a reduction in the daily range. The insulating effect, in the case of extreme high temperatures, allows the inside of the container to remain cooler than the outside and in the case of extreme low temperatures, the container will remain warmer than the outside. The second effect, the reduction of the daily temperature variation, is achieved by moderating the extreme inside temperature of the container and keeping the product at a stable level. This also helps by reducing the movement of the cork given by the expansion and contraction of the liquid inside the bottle, which can lead to the displacement of the cork and could end in wine being expelled from the bottle. Finally the spilled wine can damage other boxes and labels, which will render the whole container of wine unsuitable for the market.

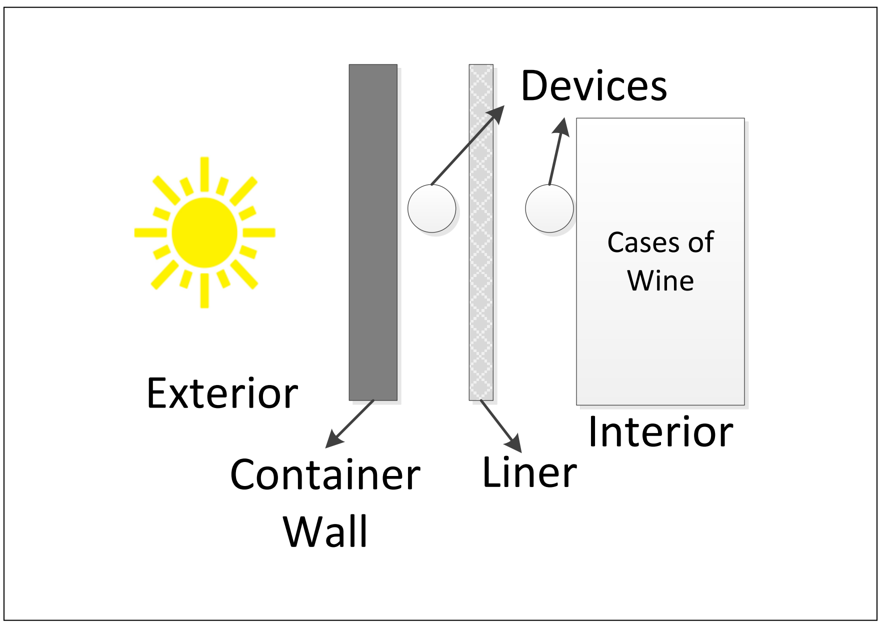


Figure 31: Diagram of device placement.

To determine the effectiveness of the liner we installed two or more temperature recording devices per container in a number of shipments from different origins to the US. As shown in Figure 31, one of the devices is set between the wall of the container and the liner and the other is set inside the container, between the linear and the cargo. The objective of the device set between the wall of the container and the liner is to determine the temperature to which the cargo would have been exposed without the use of the liner. The objective of the one set inside, between the liner and the cargo is to capture the internal temperature of the container. Both devices are set to record the temperature at the same interval, so readings could be compared.

3.2 Inside and outside temperature results

Table 17 shows the number of quilted containers for which we tracked both internal and external temperatures by their country of origin. A large percentage of the containers (71.5%) are from Chile, followed by Australia with 23.9% and Argentina with 4.9%.

Table 17: Number of containers equipped with liner by country of origin.

Country	Number	Percentage
Argentina	6	4.9%
Australia	29	23.6%
Chile	88	71.5%
Total	123	100.0%

Table 18 shows the summary statistics for the inside and outside liner temperatures. The buffering effect of the liner is reflected by the inside temperature being less variable than the outside. This effect can also be observed in the reduction of extreme temperatures (minimum and maximum).

Table 18: Inside and outside container temperatures descriptive statistics.

	Outside °C	Inside °C
Max	59.00	44.00
Mean	21.04	20.63
Median	21.00	20.50
Min	-9.50	-4.00
Std Dev	7.29	6.02
Upper quartile	26.00	25.50
Lower quartile	16.00	16.00
N	107,495	107,495

Figure 32 shows the correlation between the temperatures. If the liner had no regulating effect on the temperature, the inside temperatures of the liner would be exactly the same as the temperatures outside, indicating perfect conduction of heat, so the points on the graph would be located along the diagonal line given by $y = x$ (No–effect line). Since the liner is expected to have a dampening effect on the temperature changes, for high temperatures we expect that the points to lie below the no-effect line and for the lower temperatures, we expect the points to lie above the no-effect line.

We performed a linear regression on the internal and external liner temperatures and the resulting equation is:

$$T^{\circ}_{in}C = \underset{(0.0243)}{4.9745} + \underset{(0.001)}{0.744} \times T^{\circ}_{out}C \qquad \begin{array}{c} R^2 = 0.811 \\ F = 461,304 \end{array} \tag{3}$$

All of the parameters of the equation 3 are significant at a 99% confidence level with an R^2 of 0.811. With a 95% confidence level, the resulting equation is different from the no-effect line. If we would like to quantify the protective effect of the liner, at an external temperature of 40 °C, the liner will provide a protection by keeping the internal temperature at an average of 5.27 °C lower than the external. For the low temperature ranges, if the outside temperature would be 0 °C the inside temperature would have been on average 4.97 °C higher. So the liner is effective in insulating from extreme external temperatures.

3.3 Temperature range

The daily temperature variability is also an important danger for wine, because the contraction and expansion of the liquid can induce cork displacement. Does the liner have any effect in reducing the daily temperature range? Table 19 shows that for the containers that had a liner installed, the mean inside and outside temperature range have considerable differences. Results indicate that the inside temperature has

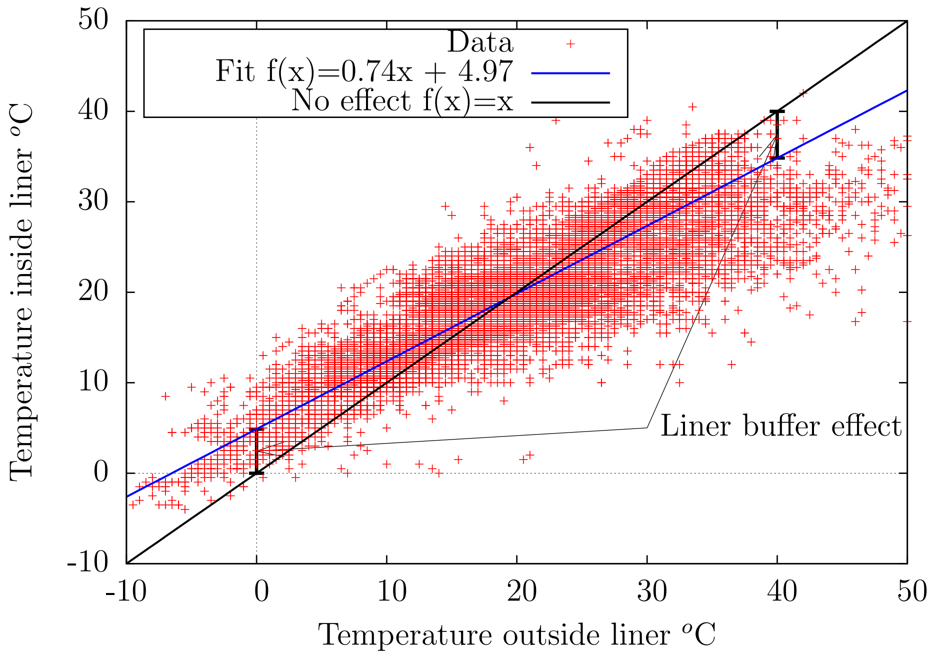


Figure 32: Inside vs outside liner temperatures.

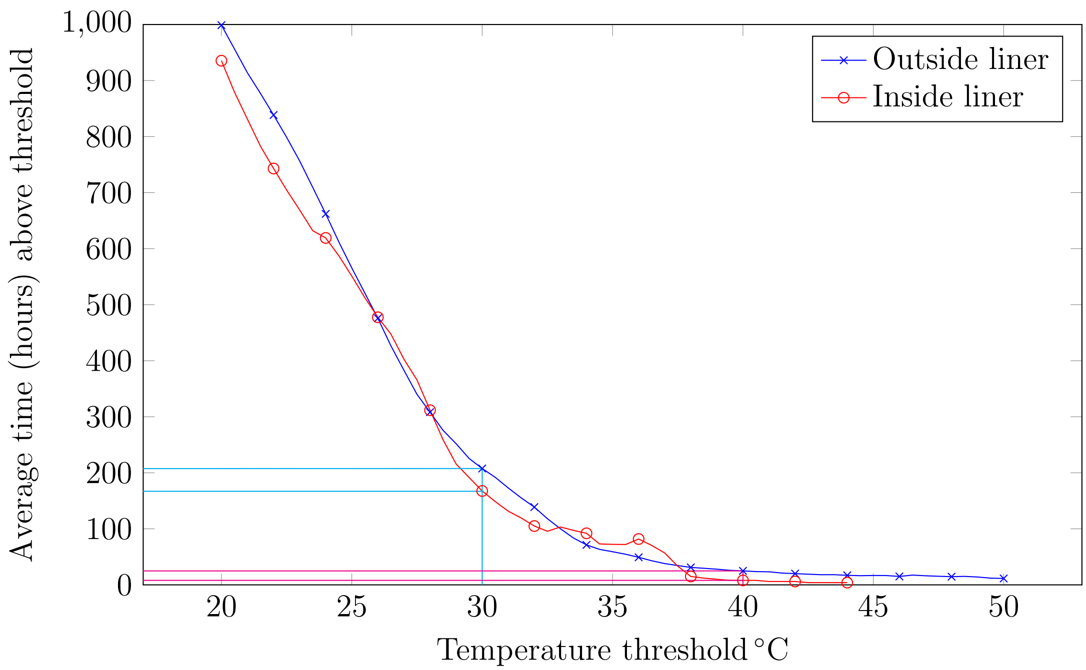


Figure 33: Average time (hours) that the devices were above threshold. Inside and outside the liner.

on average a smaller range compared to the outside. It is also interesting that the standard deviation of the daily range is also reduced, indicating a clear buffering effect of the liner.

Table 19: Inside and outside daily temperature range descriptive statistics.

	Outside daily range °C	Inside daily range °C
Max	40.50	26.50
Mean	6.20	2.24
Median	3.50	1.50
Min	0.00	0.00
Std Dev	6.65	2.45
Upper quartile	9.00	3.00
Lower quartile	1.50	0.50
N	4,570	4,570

To quantify the buffering capabilities of the liner on daily temperature range we will correlate the outside versus the inside daily temperature ranges (Figure 34). If the liner had no effect on the temperature range, the data would concentrated near the line given by $y = x$ (No Effect line), indicating that the outside range is the same as the inside range.

We performed a linear regression and obtained the equation $f(x) = 0.7643 + 0.2378x$, with all parameters representative at a 99% confidence and an R^2 of 0.415. Since this regression is statistically different from the no-effect line, the liner has a significant effect in reducing the daily temperature range inside the container, reducing the daily range to just 23.7% of its magnitude on average. As the daily temperature range increases we can see that the liner has a significant effect in moderating the extreme daily temperature. So the protection against daily spikes is continuous, while the protection against continued high temperatures dissipates as the internal and external temperatures equalizes.

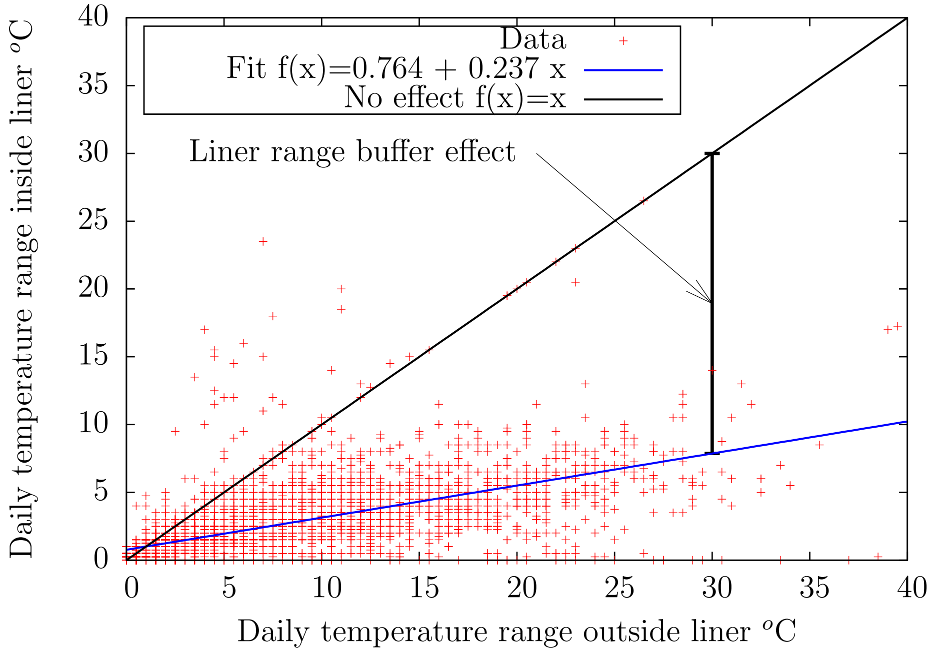


Figure 34: Daily temperatures range outside vs inside the liner.

3.4 Effect of liner during the different transport phases

Figure 35 shows the correlation graphs for the outside and inside temperatures at the different stages of transportation, the no–effect line and linear regression. All of the equations and parameters are significant at a 99% of confidence. All the estimated parameters differ from the no–effect line ($y = x$) and also all of the slope parameters are less than 1, so we can infer that the liner has a buffering effect on the extreme temperatures for all phases.

To determine if the liner effect differs at different phases of transport, we need to determine if the slope of the regressions differ. We performed an ANCOVA difference analysis and all slope responses were statistically different at a 95% confidence interval, for each phase of transport. The difference in the responses of the liner can be explained by the different temperature patterns among the phases in transport, which affect the internal temperatures of the container. The liner will be more effective in buffering under strong daily temperature variations (winery to port and

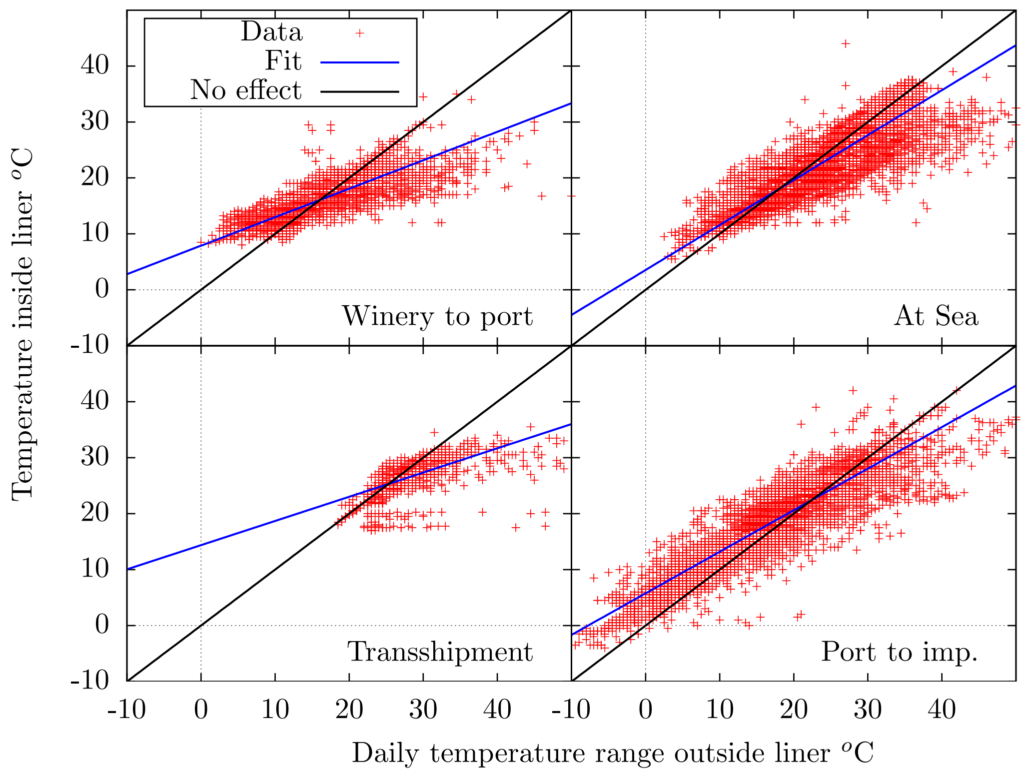


Figure 35: Temperatures outside vs inside the liner by transport phase.

transshipment) and less effective under stable temperature conditions (at sea).

Figure 35 shows the relation between the inside and outside temperature at a given moment of time. The smallest slope and therefore the biggest difference between inside and outside temperatures, is at the transshipment phase, with a value of 0.331. The second smallest slope is at the phase from the winery to the port, with a value of 0.441, followed by the destination port to importer phase, with a value of 0.687, and the last one is the at sea phase, with a value of 0.731. These values show that the liner will be needed in those phases in which daily temperatures are more variable, like the transshipment and winery-to-port phases.

Figure 36 shows the correlation between the inside and outside daily temperature range by transport phase. Table 21 shows the interaction effects for the different phases. From these results we can observe that at a confidence level of 95%, the liner range buffering effect is not different between the transshipment and the port

Table 20: Results for interaction effect of inside vs outside container liner temperatures by phase in transport.

Term	Estimate	Std Error	t Ratio	Prob> |t|
Intercept	8.358	0.065	129.250	<.0001
Winery to port	-2.470	0.027	-91.250	<.0001
At Sea	-0.620	0.021	-28.880	<.0001
Transshipment	2.795	0.055	50.800	<.0001
Outside Temp.	0.604	0.002	247.180	<.0001
Winery to port *(T Outside-20.9723)	-0.097	0.004	-27.780	<.0001
At Sea *(T Outside-20.9723)	0.197	0.003	72.480	<.0001
Transshipment(T Outside-20.9723)	-0.234	0.007	-35.400	<.0001

to importer/distributor phase. For the winery to port and at sea phases the effects are different at a 95% significance level.

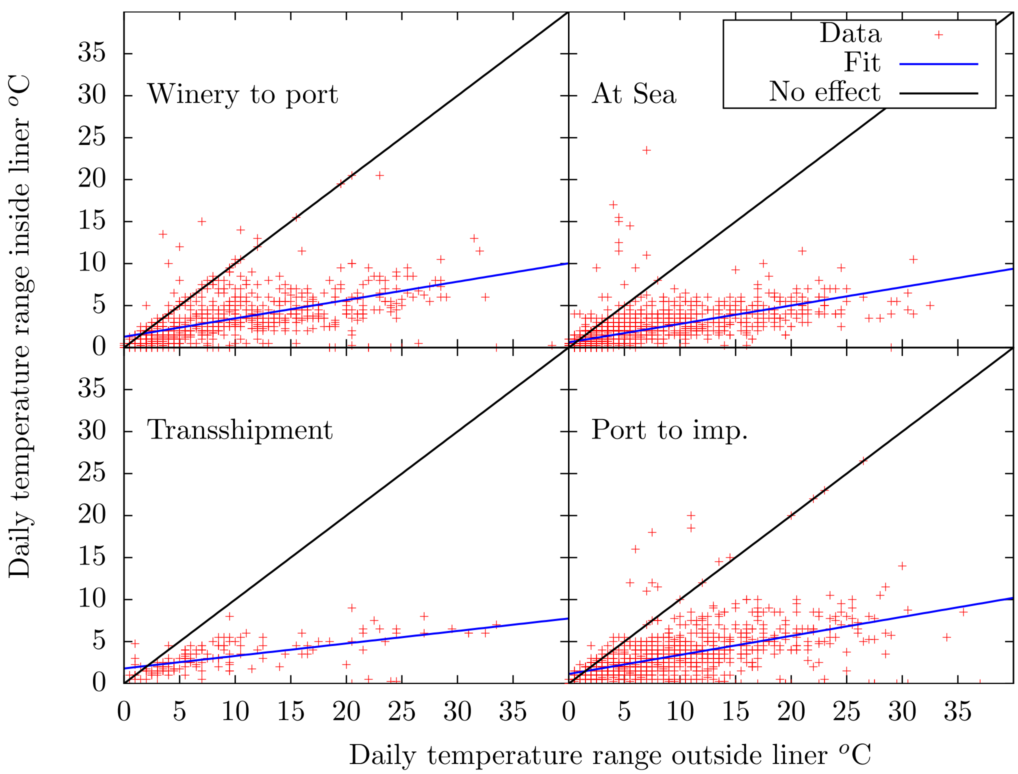


Figure 36: daily temperature range inside vs outside container liner by phase of transport.

When looking at effect of the liner at the different phases of transport, we can observe that the liner is very effective in reducing the extreme temperature risks

Table 21: Results for interaction effect of daily temperature ranges inside vs outside container by transport phase.

Term	Estimate	Std Error	t Ratio	Prob>t
Intercept	1.2136831	0.073771	16.45	<.0001
Winery to port	0.1687066	0.072442	2.33	0.0199
At Sea	-0.489031	0.0592	-8.26	<.0001
Transshipment	0.2452818	0.130376	1.88	0.06
Outside Range T	0.2032614	0.00635	32.01	<.0001
Winery to port *(R Outside-6.249)	0.0153823	0.00934	1.65	0.0997
At Sea *(R Outside-6.249)	0.015864	0.008329	1.9	0.0569
Transshipment(R Outside-6.249)	-0.054487	0.01559	-3.49	0.0005

and daily ranges at the transshipment, winery to port and destination port to importer/distributor phase. The liner buffering effect is not so significant at the at-sea phase, because of the reduced daily variability in temperature, because the internal and external temperatures tend to equalize.

3.5 Is the liner effective in buffering temperature?

The liner has two important moderating effects: first, in the case of high temperatures, it keeps the internal temperature lower and in the case of low temperatures, it keeps the internal temperature higher; second, the liner also reduces the daily temperature range, keeping a more stable temperature in the inside. So when looking at the decision to instrument a shipment with a liner, we should first determine if the route is exposed to extreme high temperatures on extended periods of time and second, if the daily temperature ranges are important. For both cases the liner will help us to protect the wine from the extreme conditions.

The liner will not be helpful in those cases were temperatures are high and stable, because the internal temperature of will equalize with the external. This is the situation happens at sea phase when the container is covered with other units. In this case we generally observe a very stable temperature pattern, so finally the internal and external temperatures will equalize. Nevertheless, we have observed sea temperature patterns that present very strong day and night variations, which is an indication that the unit is located in a position were it is exposed to direct sunlight. For these cases the liner will protect the cargo from the strong day and night temperature variations.

CHAPTER IV

THE EFFECT OF TEMPERATURE ON THE QUALITY OF WINE AS PERCEIVED BY CUSTOMERS.

4.1 Introduction

Ough [85] is the first researcher to report on the effects of temperature during transportation of wine. In his work he analyzes the effect of three stable temperature patterns (10°C, 28°C,32°C, 38°C, 43°C and 47°C) and different treatments of sulfur dioxide (SO_2), used in wine as an antimicrobial agent and antioxidant, over the chemical composition of wine. He observed that color will change under extreme temperatures, specifically white color will increase and red color will decrease. Second, the use of SO_2 in the wine acts as a temperature protector of the wine, reducing the change of the product. Third, he performed expert panel tastings of wines that were exposed to the stable temperature patterns under controlled conditions. The panel regarded the wines that were exposed to 32°C and 38°C with a maximum rating, compared to the ones set at 28°C, 43°C and 47°C that received lower ratings. So the extreme temperature exposure did not "damage" the wine as was initially expected.

Robinson et al. [95], Hopfer et al. ([56] and [55]) are the first ones to assess the sensory changes in wines under conditions that would potentially be experienced by wines during their transportation. Hopfer et al. analyzed the effect of stable temperature patterns and different types of packaging for Cabernet Sauvignon [55] and Chardonnay [56]. Robinson et al. evaluated 32 wines using sensory descriptive analysis from a group of trained panelists (oenologists), that rated white and red wines on 14 and 23 attributes, respectively. In all of the studies the sensory and analytic results showed significant differences among the wines stored at the higher temperatures. When chemical analyses were performed on treated wines, results showed differences for a number of taste compounds which are characteristic of aged wines, which suggests that high temperatures induced an accelerated aging.

None of the studies mentioned before uses *actual* transportation temperatures patterns in the treatment of their wines. They either use stable temperature patterns or for [95], which is the closest to replicate a transport situation, they put a case of wine the trunk of a car of a UC Davis professor for two weeks to simulate transport conditions.

Butzke et al. [22] is the only study which reports on *actual* transportation temperatures of shipments within the US. To analyze the effect of transportation, they quantified the formation of ethyl carbamate, also known as urethane, as a proxy for wine quality and heat exposure. No tasting or qualitative judgment was performed on the wines to determine the effect of transportation on the quality of the product.

Our contribution is first, to subject wines to *actual* historical temperature patterns encountered during international shipping and second, to evaluate the wine through blind tastings by expert purchasers. Previous studies have been anecdotal in their reports of international shipping temperatures and they have not studied the impact of *"actual simulated"* on the preferences of experts purchasers. The importance of using expert wine buyers and not oenologists, is that the buyers are the ones who make the decision to carry a certain brand of wine in their portfolio, so they act as the key-master to the market and can determine the economic success or failure of a winery.

To determine the effect of temperature on the perceived quality of wine we performed a series of blind tastings with consumers of wine who are in charge of deciding which wine to buy for their institutions. To contrast the effect of shipping temperature we used a bottle that had been subjected to a representative pattern of international shipping temperatures and compared it with the same wine that had been kept under controlled conditions. We have defined the following research hypothesis:

Hypothesis 1. *The temperature has an effect on perception of the wine by the buyer and consumer.*

This hypothesis looks to determine if the taster is able to detect the changes that the wine has gone due to extreme temperatures during transport.

Hypothesis 2. *The quality of the wine has an effect on the perception of the temperature effect by the buyer and consumer.*

We expect to determine if the "quality" of the wine determines the perception of the temperature effect by the taster. The definition of "quality" is given by the retail price of the wine which is closely correlated [99]. We can consider the "higher" quality wines as those above $ 60 dollar the bottle retail price and a score above 90 points of *Parker's Wine Buyer's Guide* [89]. We considered the "lower" quality ones to be those below $10 dollar the bottle and generally are not scored.

Hypothesis 3. *The temperature changes are more noticeable in wines that have been aged.*

If a wine has been affected by extreme temperatures, according to Castellari et al. [24], the aging process will intensify certain characteristics of the product. To determine if the exposure to extreme temperature has any effect on aging of a wine, we will take a wine that has been exposed to extreme temperatures and one that has been kept under controlled conditions, and age them both for a period of one year.

Hypothesis 4. *Temperature exposure during international transport has a detrimental effect on the quality of the wine.*

We ask the panel for a quality judgment of the wine asking the question: which wine they prefer? The objective of this hypothesis and question is to determine if transport temperatures have either a positive or negative effect on the perceived quality of the product. The preference of the judge towards either a treated or untreated glass will determine if the temperature had an effect on the perceived quality. If preferences for treated glasses exceed a random choice process, we can indicate that there is no negative effect over the perceived "quality" of the product and there can even be an improvement due to the temperature exposure.

4.2 Replicating shipping temperatures and tasting experiment design

We developed a device to replicate the temperature patterns to which the wine was subjected. Figure 37 shows a schematic diagram of the temperature replication system that we designed and built.

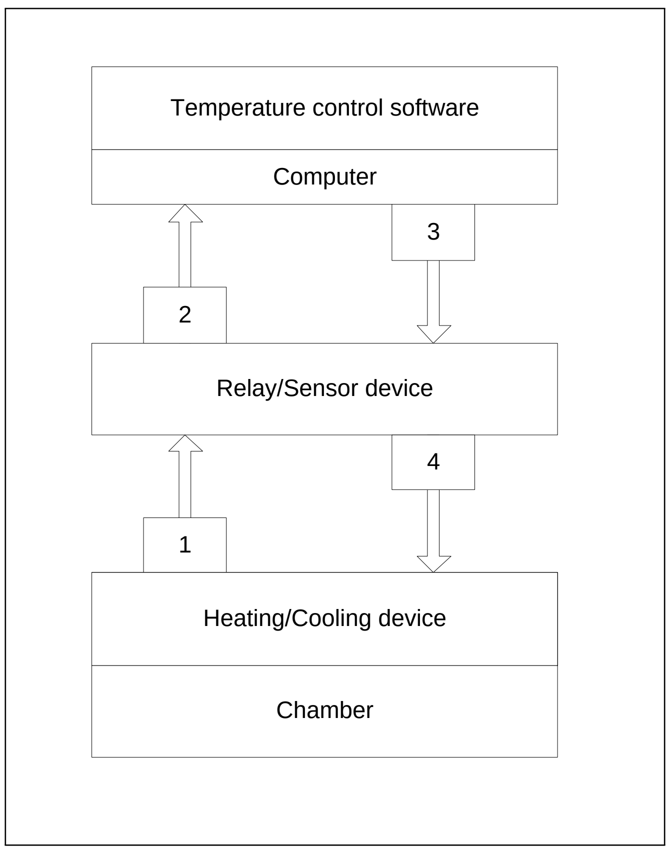


Figure 37: Diagram of the temperature replication system.

The device consists of four integrated components. The first is the heating and cooling mechanism, which is composed of a 12 volt thermoelectric cooler and warmer that can reduce the temperature to approximately to 22°C below the outside temperature and can heat up to 57°C inside. (The switch between cooling and heating is obtained by simply reversing the polarity of a thermoelectric plate.) With this device we have been able to recreate temperatures in the range of 0°C and 50°C which includes most of the observations that we have recorded in four years of tracking shipments. The second component is a four-channel temperature monitor and controller kit K190 developed by Ozitronics [87]. This consists of four DS1820 digital temperature input sensors, four relays to provide output control and one RS232 interface for reading temperatures or controlling relays from any computer by using simple text strings.

The first step in the temperature replication process is to select the temperature profile to be replicated. The sensor reads the temperature inside the cooling/heating device (1), the relay/sensor device sends the temperature to the computer (2). The computer takes an average of the temperature of the sensors and compares this temperature with the pattern at the given time. If this average is below 0.5°C of the target temperature, it sends a signal to the relay/sensor device (3) to activate the heating mechanism (4) until the temperature has reached 0.5°C over the target temperature. The converse is done in case the temperature is 0.5°C over the objective. By this mechanism the temperature is kept always within the interval of ±0.5°C of the pattern temperature. This enables us to subject the wine to arbitrary temperature trajectories, including those recorded historically, since we subject the wine to the same air temperature as was recorded during an actual shipment.

4.3 Tasting experiment

In the tasting experiment each taster was presented with three glasses of wine to taste that randomly contained wine that had either been kept under controlled conditions or had been subjected to shipping temperatures. The pour pattern was chosen at random, from a universe of eight equally likely pouring patterns, unknown to the taster as shown in Figure 38.

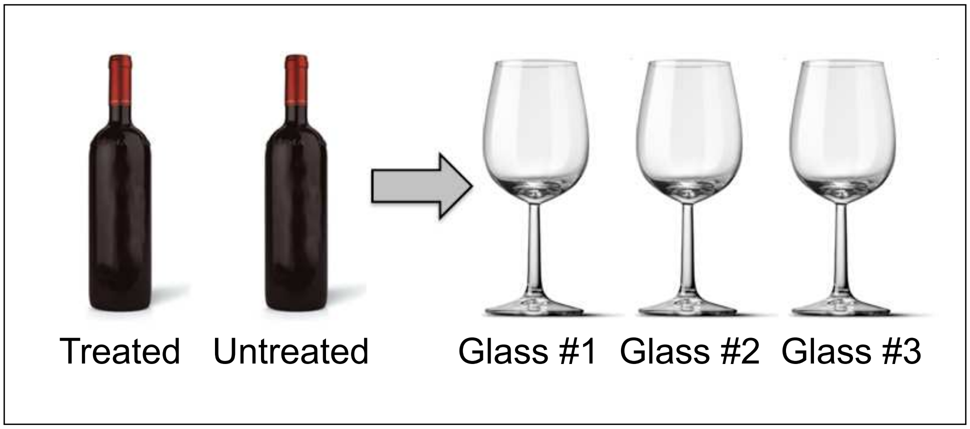


Figure 38: Experiment design. Eight equally likely pouring patterns.

Table 22 show the different colors, variety and price range of wines used in the tasting experiment. The objective behind the choices of wines was first, to determine if there are certain types of varieties that are more susceptible to heat exposure than others and second, to test whether wines of a certain “quality” are more susceptible to temperature damage.

After tasting the wines, each member of the panel was presented with the following three questions:

1. Which glass, if any, tastes different from the others?
2. Which glass(es) tastes better? Please explain in what way it is better.
3. In your opinion, which glass(es), if any, hold wine that was subjected to shipping temperatures?

Table 23 shows information of the experiment and a description of the random pouring patterns used for the different tasting experiments.

Table 22: Color, variety and price range of wine used in tasting experiment.

Color	Variety	Price range
White	Chardonnay	$< \$10$
		\$10 to \$30
		$> \$60$
White	Sauvignon Blanc	$< \$10$
		\$10 to \$30
		$> \$60$
White	Riesling	$> \$60$
White	Zinfandell	$< \$10$
Red	Cabernet Sauvignon	$< \$10$
		\$10 to \$30
		$> \$60$
Red	Merlot	$< \$10$
		\$10 to \$30
		$> \$60$
Red	Carmenere	$< \$10$
		\$10 to \$30
Red	Pinot Noir	\$10 to \$30
		$> \$60$
Champagne		$> \$60$

Table 23: Wine tasting experiment summary: Number of red or white wines tasted and number of tasters on each experiment. Characteristics and number of pouring patterns given to tasters: pouring pattern contained one different glass with untreated wine, pouring pattern contained one different glass with treated wine, pouring pattern contained only treated wines, pouring pattern contained only treated wines

Experiment		# of Wines	Total # of Tasters	Characteristics and number of pouring patterns: One different Untreated glass	One different Treated glass	All untreated	All treated
Wines 1.5 Lt.	White	2	8	9	5	1	1
	Red	3	8	10	9	1	4
	Total	5	8	19	14	2	5
Wines < $10	Whites	4	5	12	7	0	1
	Red	4	5	8	7	3	2
	Total	8	5	20	14	3	3
Wines < $10 Aged 1 yr.	Whites	3	6	8	8	0	2
	Red	3	6	7	7	0	4
	Total	6	6	15	15	0	6
Wines $10 - $ 30	Whites	3	5	6	7	1	1
	Red	3	5	5	5	2	3
	Total	6	5	11	12	3	4
Wines > $ 60	Champ.	2	5	5	4	1	0
	Red	2	5	3	4	1	2
	Total	4	5	8	8	2	2

4.4 *Tasting results*

Our experiment composed of 3 glasses with equal probability of having either treated or untreated wine. According to the pouring pattern. the taster could correctly indicate that one of the three glasses contained a different wine or all glasses had the same wine. Hence the sample space for this experiment is 4 and so the probability to randomly select the correct glass is $1/4 = 25\%$

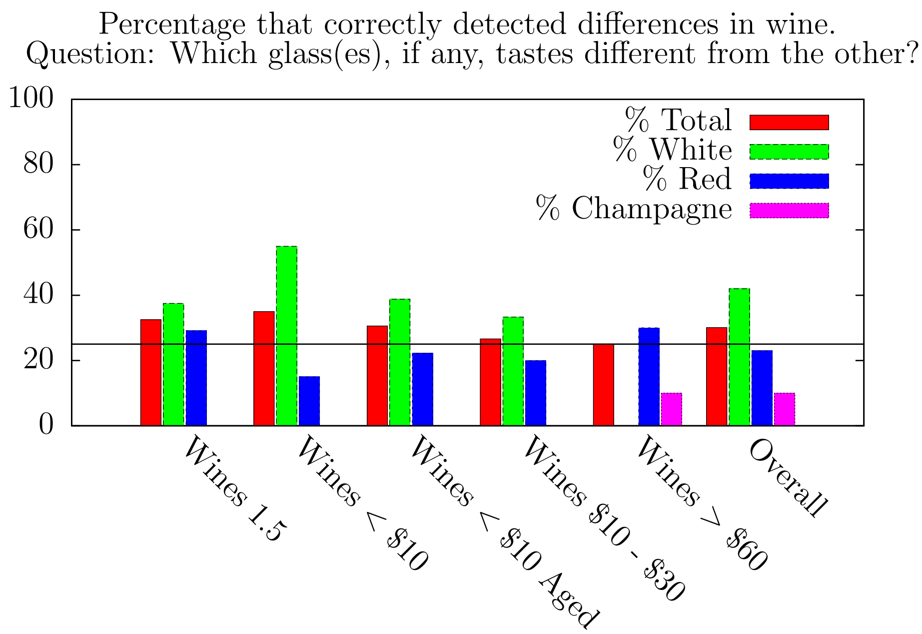


Figure 39: Results Question: Which glass, if any, tastes different from the other?

Table 24: Results question: Which glass, if any, tastes different from the other? Values indicate percentage of judges that correctly: detected the different glass, detected the untreated glass or detected the treated glass. Values between parenthesis indicate number of judges.

Experiment		Detected correctly the different glass.	Detected correctly untreated glass diff.	Detected correctly treated glass diff.
Wines 1.5 Lt.	Whites % (N)	37.5 % (6)	33.3 % (3)	60.0 % (3)
	Red % (N)	29.1 % (7)	50.0 % (5)	22.2 % (2)
	Total % (N)	32.5 % (13)	42.1 % (8)	35.7% (5)
Wines < $10	Whites % (N)	55.0 % (11)	50.0 % (6)	71.0 % (5)
	Red % (N)	15.0 % (3)	25.0 % (2)	14.0 % (1)
	Total % (N)	35.0 % (14)	40.0 % (8)	42.8 % (6)
Wines < $10 Aged 1 yr.	Whites % (N)	38.8 % (7)	37.5 % (3)	50.0 % (4)
	Red % (N)	22.2 % (4)	28.6 % (2)	14.2 % (1)
	Total % (N)	30.6 % (11)	33.3 % (5)	33.3 % (5)
Wines $10 - $ 30	Whites % (N)	33.3 % (5)	33.3 % (2)	42.8 % (3)
	Red % (N)	20.0 % (3)	20.0 % (1)	40.0 % (2)
	Total % (N)	26.6 % (8)	27.3 % (3)	41.6 % (5)
Wines > $ 60	Champ % (N)	10.0 % (1)	20.0 % (1)	0.0 % (0)
	Red % (N)	30.0 % (3)	33.3 % (1)	50.0 % (2)
	Total % (N)	25.0 % (5)	25.0 % (2)	50.0 % (2)
Overall	Whites % (N)	42.0 % (29)	40.0 % (14)	55.5 % (15)
	Reds % (N)	23.0 % (20)	33.3 % (11)	32.0 % (8)
	Champ % (N)	10.0 % (1)	20.0 % (1)	0.0 % (0)
	Total % (N)	30.1 % (50)	35.6 % (26)	41.1 % (23)

Table 24 and Graph 39 presents the results for the question: Which glass(es), if any, tastes different from the others? For most of the white wines the percentages were above the random level of 25%, which is an indication that the judges were able to correctly detect the differences in white wines. The highest ability to detect the different glass was on the white wines below $10 with a detection of the different glass in 55% of the cases. As the price or quality of the white wines increased, the ability to detect the different glass is reduced. For red wines, the judges were below the random level, with the exception of the high quality and the 1.5 liters which were above. For the other red wines, they were in all the cases below the random level. This suggests that the judges are unable to detect for the the red wines which glasses contained treated or untreated wine.

If we compare the case in which the bottles were kept for one year with the one that was not aged, for white wines, aging of the wine reduces the ability to detect the different glass. This reduction in the overall capacity of judges to detect the differences, can be attributed to the fact that wines below $10 per bottle are not meant to be aged and are designed to be served young; so the aging of white wines was detrimental for the "non treated" wine. Another factor that can affect the judgment of aging is that the wines compared are not exactly the same because the aged wine is from the vintage of the previous year. Nevertheless, different vintages can be considered comparable since a $10 per bottle wine is very consistent in their attributes from one vintage to the next [25, 98].

To analyze the question: Which glass(es) taste better? and determine if the judges prefer the untreated or treated wines, we compared our tasting results with a random choice process. For every pour pattern there are 8 different possible glass choices that the judge can make. For the case when the pour pattern contains only untreated wines, the judge will prefer an untreated glass in 7 choice patterns, there is only one case in which he will not prefer the untreated wine: none of the glasses are preferred.

Another situation is that if only one glass contains treated wine, there will be three possible choices in which the judge will only prefer untreated wines. If two glasses contain treated wine, there will only be one case were he selects the untreated wine. If we analyze all situations and take all the favorable cases (untreated wine selected), there are 20 situations in which the judge may prefer only glass(es) with untreated wine in a sample space of 64 possible cases. So if the judges would randomly select the untreated wine, they will only select untreated glasses in $20/64 = 31.25\%$ of the cases. The same percentage of occurrence will apply if we take the favorable case as choosing the treated wine.

Table 25 shows the overall results for the second question: Which glass(es) taste better? Figure 40 presents the results for white wines, indicating that the judges showed a consistent preference for the glasses that contained the treated wine, since all of their preferences were above the level of 31.25%. For the case of untreated glasses the preferences were below the 31.25%, with the exception of the 1.5 Lt., confirming the observation that judges had a non-random preference for treated wine. For red wines (Figure 41), the preference towards either treated or untreated wine is not clear. Judges preferred the treated glasses for the 1.5 liter and the wines below \$10 aged. But for the ones between \$10 - \$30 and above \$60, the judges preferred both treated and untreated wines above the random level.

Table 25: Results question: Which glass(es) taste better? Values indicate percentage of judges that selected: at least one treated glass, selected only treated glass(es) or selected only untreated glass(es). Values between parentheses indicate number of judges.

Experiment		Selected at least one treated glass	Selected only treated wines	Selected only untreated wines	No Choice
Wines 1.5 Lt.	Whites % (N)	43.7 % (7)	33.3 % (6)	50 % (8)	6.25 % (1)
	Red % (N)	62.5 % (15)	45.8 % (11)	29.1 % (7)	8.3 % (2)
	Total % (N)	55 % (22)	42.5 % (17)	37.5 % (15)	7.5 % (3)
Wines < $10	Whites % (N)	75 % (15)	50 % (10)	20% (4)	5 % (1)
	Red % (N)	50 % (10)	20 % (4)	25 % (5)	25 % (5)
	Total % (N)	62.5 % (25)	35 % (14)	22.5 % (9)	15 % (6)
Wines < $10 Aged 1 yr.	Whites % (N)	72.2 % (13)	44.4 % (8)	5.6 % (1)	22.2 % (4)
	Red % (N)	77.7 % (14)	38.8 % (7)	5.6 % (1)	16.7 % (3)
	Total % (N)	75% (27)	41.7 % (15)	5.6 % (2)	19.4 % (7)
Wines $10 - $ 30	Whites % (N)	80 % (12)	53.3 % (8)	20 % (3)	0 % (0)
	Red % (N)	53.3 % (8)	46.7 % (7)	40 % (6)	6.7 % (1)
	Total % (N)	66.6 % (20)	50 % (15)	30 % (9)	3.3 % (1)
Wines > $ 60	Champ % (N)	60 % (6)	30 % (3)	20 % (2)	20 % (2)
	Red % (N)	40 % (4)	40 % (4)	60 % (6)	0 % (0)
	Total % (N)	50 % (10)	35 % (7)	40 % (8)	10 % (2)
Overall	Whites % (N)	68.1 % (47)	46.4 % (32)	23.2 % (16)	8.7 % (6)
	Reds % (N)	58.6 % (51)	37.9 % (33)	28.7 % (25)	12.6 % (11)
	Champ % (N)	60 % (6)	30 % (3)	20 % (2)	20 % (2)
	Total % (N)	62.6 % (104)	41 % (68)	25.9 % (43)	11.5 % (19)

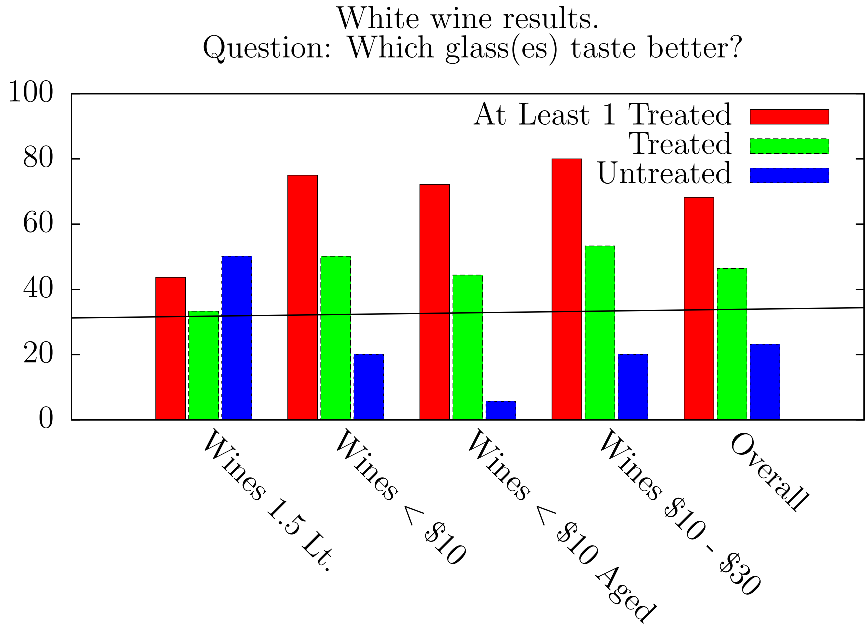


Figure 40: White wine results. Question: Which glass(es) taste better?

When the judges were presented with the tasting results they said that they were "surprised" by the results. Because they expected that heat would greatly affect the white wines by reducing their acidity and fruitiness. A possible explanation for this result is that the temperature pattern that the wines were subjected to produces an accelerated aging of the wine, which appealed to the tasters.

Table 26 shows the results for the question: In your opinion, which glass(es), if any, hold wine that was subjected to shipping temperatures? Since our focus was in determining if the judges were able to detect the "treated" glasses, we present the aggregated results in Table 27 with the judges that selected only treated glass(es), selected at least one untreated glass or selected only untreated glass(es).

In Figure 42 and Figure 43 we compare the tasting results for white and red wine respectively. For white wines we can observe that the judges were unable to correctly point out the glass(es) that contained the treated wine and on the contrary, they indicated the untreated glasses as the ones subjected to the shipping temperatures. The

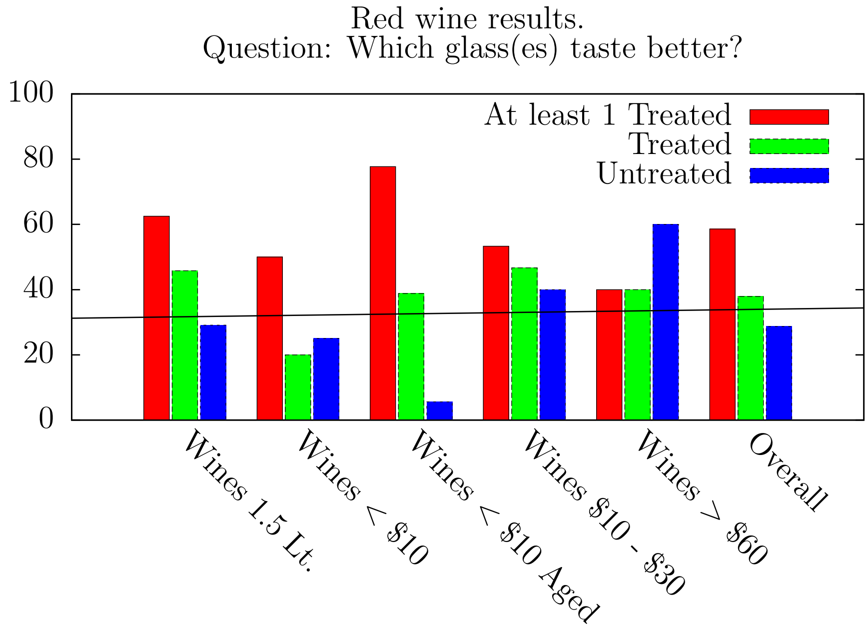


Figure 41: Red wine results. Question: Which glass(es) taste better?

only exceptions werte the 1.5 liter white wines, where the judges correctly identified the glasses that contained the treated wines.

For the red wines the judges correctly chose the glass(es) that contained the treated wine in all of the cases. For the wines above $60, the judges clearly pointed out the treated glass(es). In the other types of wines the judges selected at least one untreated glass(es) above the random choice threshold, which suggests that the judges are also unable to detect which glass(es) contained the wine that was treated. The inability of the judges to determine the glass(es) that contained the wine that was subjected to shipping temperatures reinforced the previous finding that they were unable to detect the glass that was different.

Table 26: Results question: In your opinion, which glass(es), if any, hold wine that was subjected to shipping temperatures?

Experiment		Selected at least one untreated glass	Selected only treated wines	Selected only untreated wines	No Choice	No Choice had Treated
Wines 1.5 Lt.	Whites % (N)	43.7 % (7)	33.3 % (6)	25 % (4)	18.8 % (3)	6.25% (1)
	Red % (N)	45.8 % (11)	41.7 % (10)	37.5 % (9)	12.5 % (3)	12.5 % (3)
	Total % (N)	45 % (18)	40 % (16)	32.5 % (13)	15 % (6)	10 % (4)
Wines < $10	Whites % (N)	55% (11)	35% (7)	50% (10)	5 % (2)	5 % (2)
	Red % (N)	30 % (6)	35 % (7)	25 % (5)	35 % (7)	30 % (6)
	Total % (N)	42.5 % (17)	35 % (14)	37.5 % (15)	22.5 % (9)	20 % (8)
Wines < $10 Aged 1 yr.	Whites % (N)	44.4 % (8)	27.8 % (5)	33.3 % (6)	27.7 % (5)	27.7 % (5)
	Red % (N)	33.3 % (6)	33.3 % (6)	27.8 % (5)	33.3 % (6)	33.3 % (6)
	Total % (N)	38.9 % (14)	30.6 % (11)	30.6 % (11)	30.6 % (11)	30.6 % (11)
Wines $10 - $ 30	Whites % (N)	60 % (9)	33.3 % (5)	46.6% (7)	13.3 % (2)	13.3 % (2)
	Red % (N)	60 % (9)	33.3 % (5)	26.7 % (4)	6.7 % (1)	6.7 % (1)
	Total % (N)	60 % (18)	33.3 % (10)	36.6 % (11)	10 % (3)	10 % (3)
Wines > $ 60	Champ % (N)	70 % (7)	10 % (1)	50% (5)	20 % (2)	20 % (2)
	Red % (N)	40 % (4)	60 % (6)	10% (1)	0 % (0)	0 % (0)
	Total % (N)	50 % (10)	35 % (7)	30 % (6)	10 % (2)	10 % (2)
Overall	Whites % (N)	50.7 % (35)	33.3 % (23)	39.1 % (27)	17.4 % (12)	14.5 % (10)
	Reds % (N)	41.3 % (36)	39.1 % (34)	27.6 % (24)	19.5 % (17)	18.4 % (16)
	Champ % (N)	70 % (7)	10 % (1)	50% (5)	20 % (2)	20 % (2)
	Total % (N)	47 % (78)	34.9 % (58)	33.7% (56)	18.17% (31)	16.8 % (28)

Table 27: Aggregated results question: In your opinion, which glass(es), if any, hold wine that was subjected to shipping temperatures?

Experiment		Selected at least one untreated glass or no choice had treated	Selected only treated wines	Selected only untreated wines
Wines 1.5 Lt.	Whites % (N)	50 % (8)	33.3 % (6)	25 % (4)
	Red % (N)	58.3 % (14)	41.7 % (10)	37.5 % (9)
	Total % (N)	55 % (22)	40 % (16)	32.5 % (13)
Wines < $10	Whites % (N)	65% (13)	35% (7)	50% (10)
	Red % (N)	60 % (12)	35 % (7)	25 % (5)
	Total % (N)	62.5 % (25)	35 % (14)	37.5 % (15)
Wines < $10 Aged 1 yr.	Whites % (N)	72.2 % (13)	27.8 % (5)	33.3 % (6)
	Red % (N)	66.6 % (12)	33.3 % (6)	27.8 % (5)
	Total % (N)	69.4 % (25)	30.6 % (11)	30.6 % (11)
Wines $10 - $ 30	Whites % (N)	73.3 % (11)	33.3 % (5)	46.6% (7)
	Red % (N)	66.7 % (10)	33.3 % (5)	26.7 % (4)
	Total % (N)	70 % (21)	33.3 % (10)	36.6 % (11)
Wines > $ 60	Champ % (N)	90 % (9)	10 % (1)	50% (5)
	Red % (N)	40 % (4)	60 % (6)	10% (1)
	Total % (N)	50 % (10)	35 % (7)	30 % (6)
Overall	Whites % (N)	66.7 % (46)	33.3 % (23)	39.1 % (27)
	Reds % (N)	60.9 % (53)	39.1 % (34)	27.6 % (24)
	Champ % (N)	70 % (7)	10 % (1)	50% (5)
	Total % (N)	65.1 % (108)	34.9 % (58)	33.7% (56)

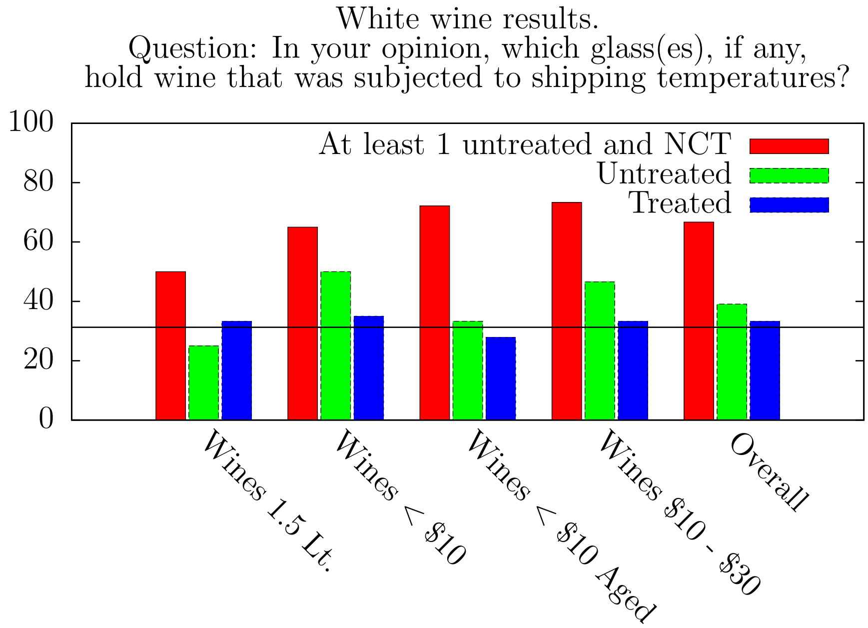


Figure 42: White wine aggregated results. Question: In your opinion, which glass(es), if any, hold wine that was subjected to shipping temperatures?

4.5 Does heat improve wine?

For white wines there is no information to reject the hypothesis 1. Temperature has an effect on the perception of the wine by the buyer and consumer, because in most cases they are able to correctly detect the glass(es) that contained the different wine. For red wines we can reject hypothesis 1, because in general judges were unable to correctly detect the glass(es) that contained the different wine. So temperature did not have an effect on the perception of red wines by the buyer and consumer. A possible explanation for this result is that a characteristic of white wines is fruity and fresh vegetal aromas, which are affected by the exposure to extreme temperatures [70]. On the other hand, red wines are characterized by a higher tannin content than white wines and also are commonly exposed to oak, which gives a protection against the effect of extreme temperatures. Robinson et al. [95] also reported a less pronounced effect of temperatures on red wines than in white.

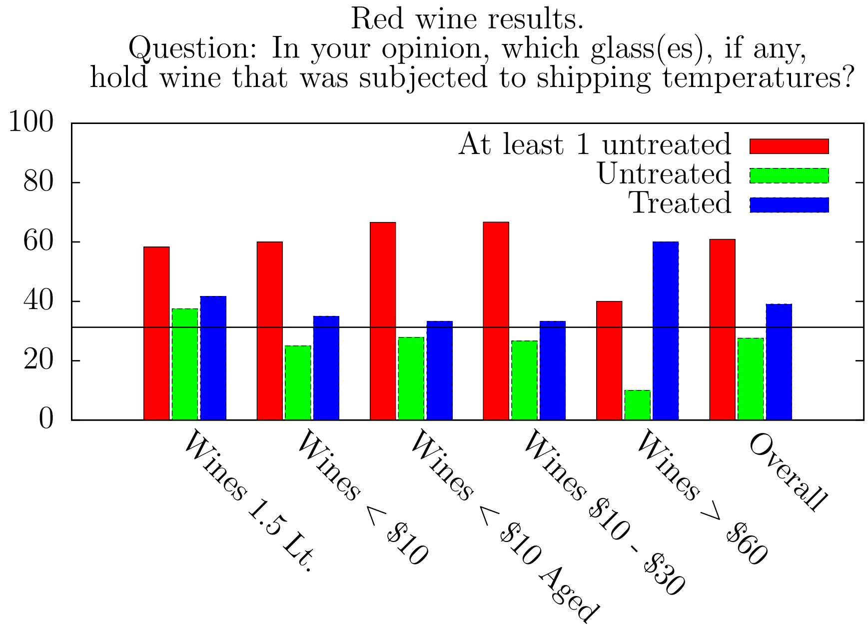


Figure 43: Red wine results. Question: In your opinion, which glass(es), if any, hold wine that was subjected to shipping temperatures?

For white wines, the quality of the wine has an impact on the perception of the temperature effect, because the percentage of judges that detected correctly the different glass(es) decreased constantly as the price of the wine was increased. For the case of red wines, since the judges were unable to detect the differences in the wines, we cannot indicate that quality has an effect on the perception.

Aging did not have either a positive or negative impact on the perception of the temperature effect on white wines. Comparing results of un-aged and aged wines the only significant difference is that the percentage of judges that correctly detected the different glass(es) was reduced. But the preferences for the treated glass and the ability to detect the glass(es) that contained the wine that was subjected to shipping temperature did not significantly change.

For white wines, the temperature pattern that we subjected the wines did not have a detrimental effect on the quality of the wine, on the contrary, judges showed a preference for the glass(es) that contained the treated wine. We cannot generalize this finding to indicate that high temperatures have a positive effect on the quality of white wines. More research, like subjecting the same type of white wines to different transportation temperature patterns and determining the impact on quality, is needed to support such a claim. Nevertheless these findings do not contradict what Ough [85] reported.

In the case of red wines we cannot make any conclusion on the effect over the perception, aging or quality, because even though judges showed a preference towards the glass(es) that contained the treated wine, they were unable to correctly detect the glass that contained the different wine.

The main implication of these results for international wine logistics is that, with our panel composed by purchasers at the consumer end of the international wine supply chain and a representative temperature transportation pattern, we did not observe a "perceptible" effect on the quality of the product. Which indicates that from a temperature perspective, the current methods of international wine logistics serve well the needs of the industry. Care must be taken to avoid physical changes of the product, as cork displacement, that can affect the quality of the product.

Finally, we only analyzed the effect of temperature on the aging of wine by keeping an untreated and treated bottle of wine for one year. Further analysis is needed to determine the effect of shipping temperatures on extended aging (more than 5 years), since high end French wines are aged for even longer periods.

CHAPTER V

SCHEDULING THE BOTTLING LINE OF A LARGE WINERY

For large wine making companies bottling the product is a critical process. It can determine the financial success or failure of a company, because it immobilizes a large amount of working capital in terms of the materials (bottle, capsule, labels and box), equipment (bottling and labeling) and labor. The bottles and packaging material can account to over 30% of the total costs of the final product [50] and bottling is a labor intensive activity, which requires crews of up to 6 workers per shift. Of course, an inefficient use of the bottling lines may also cause delays in meeting customers orders, which can lead to a possible loss of clients. All of this makes the process of planning and sequencing the bottling lines important for the success of the business.

Figure 44 shows a schematic of the stages involved in the bottling process. The process starts with empty bottles that are introduced in a machine that thoroughly cleans the inside to avoid contamination of the wine. The empty bottles then pass to another machine that fills each bottle with wine and adds inert gas to displace the remaining oxygen. The filled bottle proceeds to a machine that inserts either a cork or screw cap into the bottle. If a cork is used, the bottle passes to a machine that sets a plastic or metal capsule on the top that is heated and compressed to fit the bottle. The next step is to put the front and back labels on the bottle, which can be done either with adhesive or glue labels. Finally the bottles undergo a quality inspection, which checks that the ullage is adequate and also that the corks, capsules, and labels have been positioned correctly.

Bottling requires coordinating different areas of the company, from the acquisition

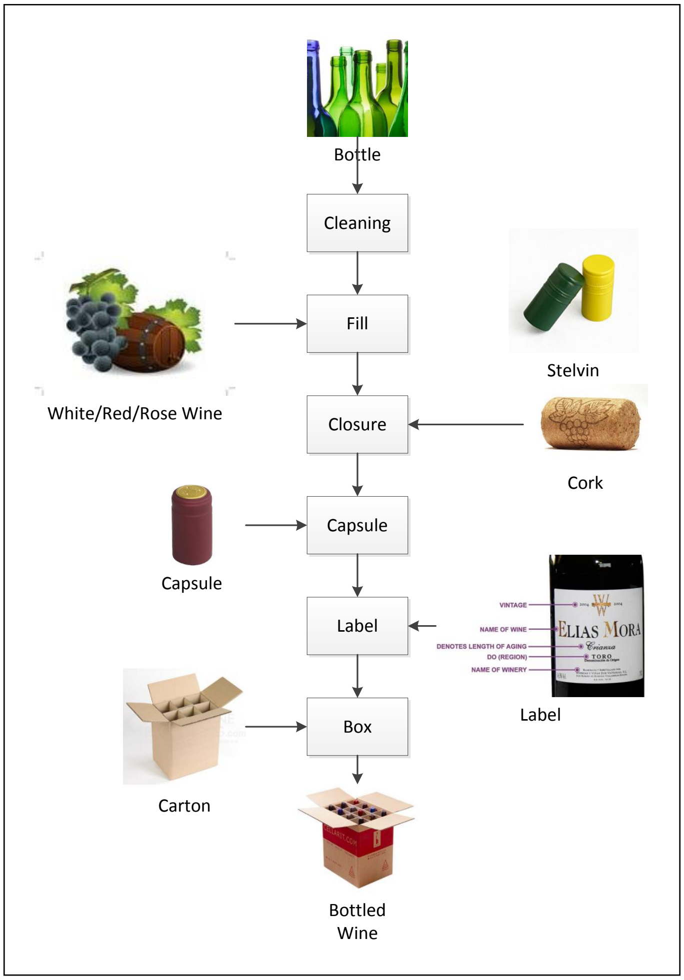


Figure 44: Stages in the bottling process.

of packaging material to the availability of bottling lines and crews. The quality of the proposed plan is determined by four indicators: demand service level, inventory costs, labor costs and line efficiency. There are trade-off among these indicators, since the product must be packaged and available on time to serve the demand or else it can affect the service level given to the customer. This will promote building up inventory of bottled wine to serve demand. On the other side, to keep costs low a good bottling plan should try to reduce the inventory of finished goods and efficiently utilize the lines and labor.

The supply chain group is in charge of planning the bottling process. It requires the following information: customer orders (type of product, quantity and time), production capacity (number of lines, rate, change-over times, labor, etc.), availability of the bottling supplies (bottle, cork, labels, capsule, and box), storage capacity and labor costs. With this information the planner attempts to build a bottling plan that will fulfill the customer demand while minimizing the production costs: inventory and labor.

When planning their bottling operations wineries can either bottle upon order or bottle to stock. In the first approach the planner generates a weekly or monthly bottling plan from historical information, which is constantly revised as customers orders arrive. The executable plan is released to the line on a bi-weekly basis and is generally significantly different from the original plan. In the bottle to stock scheme, the planner produces a monthly plan derived from demand forecast and inventory targets, with some revisions from customer demands, and is released to the line on a weekly basis and it is usually similar to the original plan.

Bottling to stock has higher inventory costs because it increases the inventory in anticipation of customer orders. However, since it has fewer and looser deadlines than bottling to order, schedules tend to be more efficient (e.g. bigger lot sizes and less frequent changeovers).

Another aspect that makes the scheduling a challenging process, is that marketing and sales department may pressure to change the schedule as new customer orders arrive and as the wine is made available by the winemakers. Figure 45 shows an example of how dynamic the bottling planning process can be. The horizontal axis corresponds to time, while the vertical lines represent the relation between the moment that the order was scheduled and the moment in which that order was bottled. If a plan were perfectly executed, that is, if the scheduled orders were performed at exactly the moment they were planned, we would observe that all of the lines would be vertical and parallel. In a real plan, we observe that in the "Executed" plan, the lines are far from being parallel and vertical. Many orders were advanced from their original scheduled date and others were delayed, indicating that the executed plan was quite different from what was originally planned.

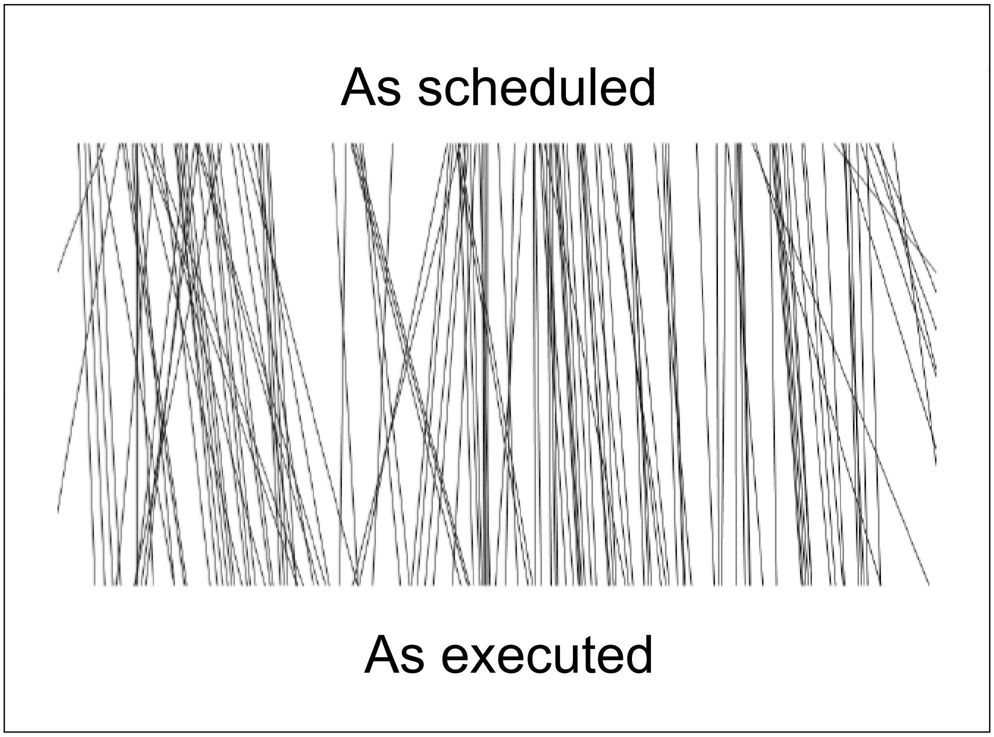


Figure 45: Perfect versus executed plan.

In large wineries, it is normal to find a large number of different Stock Keeping Units (SKUs), that need to be bottled in a given planning period. The large number of SKUs is because for a same variety (Cabernet Sauvignon, Merlot, Sauvignon Blanc, Chardonnay, etc.), quality of wine (varietal, reserve); t bottle type, size, and label. The number can be in the order of 200, which can be scheduled over multiple different bottling lines.

Typical efficiency of a wine bottling line, measured as the effective productive time versus the total available time, is in the 50% to 80% range [49]. This is due to the different types of machine setups, the number of SKUs and the constant changes in the schedules. A large amount of the non-productive time is spent on set-ups, when the line is stopped to perform configuration changes to process the next SKU. These setups can be divided into two groups: major setups, which involve a change in the type of bottle in which the wine is being bottled, and minor setups, which involve changes in the color of wine, box or the label. The minor setup changes, such as switching the carton boxes or changing the labels, may take only 25 minutes of downtime. A major set-up, such as the transition to a different bottle type, which involves a reconfiguration of the entire line, might take a whole 8 hour shift. Figure 46 shows how many types of bottles may be used to bottle only Bordeaux and Burgundy. This is an example of the wide variety of bottles that can be used.

Figure 46: Example of the different types of bottles available for Bordeaux and Burgundy family of bottles. Source: http://www.silverspurcorp.com/.

When the bottling line changes from one color of wine to another, the set-up time is dependent on what was previously processed. When the line must start bottling white wine, after bottling red wine, the line must be thoroughly cleaned. Otherwise the first batch of the bottling will be rose instead of white. When switching from white to red wine, the cleaning process may be quicker since the effect on the color is negligible.

Other aspects that need to be incorporated in the bottling plan are the regular cleaning cycles of the system. Since wine is a food product, any quality problem may be dangerous to the health of the consumer. To enforce a high quality standard, sanitation is a mandatory procedure for the line. This mandates that the bottling line cannot run continuously for more than a week without performing a deep cleaning of the system to sanitize and avoid any contamination to the wine. This will take down the line for a complete shift. Another quality procedure is the enforcement of the traceability of the product, which allows any agent of the supply chain to trace back the product for any quality issues. This imposes a constraint in the bottling process that any production run needs to start and finish within a production shift, so the production can be traced back to the crew that performed the bottling. Even if the same product is going to be processed in the next shift, there must be a pause to hand off the line to the next crew, so there is a clear differentiation between who performed each task.

Finally, the number of active shifts and crews assigned to each bottling station is another constraint that needs to be taken into account while constructing the bottling plan. Because the labor required for the bottling process requires a level of training and skills that is not easily available in the market, the number of available crews to be assigned to each shift in the bottling process acts as a limiting factor. Large wineries, which have more than one daily shift, generally handle the change in the number of available crews by, if labor laws allow it, performing a daily reassignment of them. If the reassignment is not possible, they proceed to either hire or let go crews. Both mechanisms have costs. For the the first one, there might be a cost due to a reduced productivity of the crew, and in the second case, there are costs of hiring and releasing personnel.

All of the previous characteristics, dynamic process, large number of SKU, sequence dependent set-up times, long set-up times with low utilization of lines, quality (sanitary and traceability) and labor constraints (crewing and shifts), makes this lot sizing and scheduling problem complex in its size and scope and a good candidate to develop decisions support tools that can help in the planning process.

Our research is aligned with what Clark et al. [28] presents as the challenges for lot sizing and scheduling: Coming closer to what the planner faces when scheduling the bottling line of large wineries, working with large real life instances and adding a number of variables and constraints. According to Clark et al. [28] there is a lack of research on the effect of using real life instances (some with "dirty data") to carry out computational experiments.

The research literature related to the scheduling of bottling lines is focused on the lot sizing part of the problem rather than the integration of the Simultaneous Lot Sizing and Scheduling (SLS) problems [20, 57, 61, 91]. Nevertheless, there is some work that covers the integration of lot sizing and scheduling [40, 112]. Most of the formulations and algorithms focus on single machine, so there is only reduced literature on the General lot sizing and Scheduling Problem for Parallel production with sequence dependent setup times, GLSPPL ([37, 76, 77]). Fleischmann [47] looks at a GLSPPL a for single machine and Meyr et al. [77] for multi-lines presenting formulations with discrete macroperiods that can be seen as shifts but do not incorporate the crew resource constraint.

The research presented here makes three main contributions. The first is the development of a formulation of the GLSPPL that adds important structural constraints to the system, such as the existence of major and minor setups, sanitation and traceability considerations, and shift and crewing constraints. Second, since as indicated before the bottling plan is a very dynamic process that is subject to constant rescheduling, we will present a mechanism that will add stability and robustness to the plan to minimize the impact of changes and disruptions. Finally, we develop a decomposition heuristic that uses the structure of the problem to produce "good" solutions in short periods of time. Because our heuristic decomposes the problem it can be solved in parallel, which allows significant gains in run time efficiency.

5.1 Literature review

The literature review will be divided into two sections. In the first one we will look at the different advances in the GLSPPL with sequence dependent set-up time/costs, with a special emphasis on real applications to bottling lines. The objective is to determine the best practices on modeling the problem and how they have incorporated, in the case they have, the shift and crew constraints. On the second part, we will review the different solution strategies to solve the GLSPPL.

5.1.1 Lot sizing and scheduling models

The importance of looking at the "Simultaneous Lot-sizing and Scheduling (SLS)" decisions have been demonstrated in many industries, including, yogurt packaging [72], foundries [38], electro-fused grains [69], glass container industry [6], animal feed production [107], soft drink production [45], pharmaceutical company [103], and casting operations [53]. The planning process must determine a schedule of the production orders and the lot size of the batches that will allow fulfilling the customers orders on time while keeping production costs low. Karimi et al. [61] do an extensive review of the lot sizing problem indicating that making the right decisions in lot sizing will directly affect the system performance and its productivity. Also Allahverdi et al. [4] indicate that there are important savings when setup time/costs are explicitly incorporated in scheduling decisions.

A few mixed integer programming (MIP) models for the lot-sizing and scheduling of beverages have been proposed in the literature. None of them have simultaneously integrated in their optimization models sequence dependent setup times, shift/crewing capacity constraints and costs of changing the number of them. Clark [29] presents a MIP model for the lot sizing of the production in a canning line at a drink manufacturer. His model simply minimizes the inventory and backlog costs and does not take into account sequence dependent setups, but indicates an extra fixed setup time if there is also a change in the liquid. Ferreira et al. [44] propose a synchronized two-stage lot sizing and scheduling model for a soft-drink production process. In their model they take into account sequence dependent setup times and add their costs to the objective function. But they do not take into account any crew/shift capacity constraint. Berruto et al. [15] are the only ones that present a simple model for scheduling wine bottling operations. Their model is built for a single line and multiple products, with crew capacity constraints, but only using normal and overtime hours as variables. There is no flexibility in the number of crews used.

The previously mentioned papers are all based on the GLSPPL model which was first proposed by Fleischmann and Meyr [48], later modified by Meyr [75] to capture sequence dependent times, and finally,it was expanded to capture multiple lines [76]. In their latest formulation the objective function minimizes the total costs divided into: holding costs, sequence-dependent setup costs and line specific production costs. They divide time into a fixed number of *macro-periods* that can expand for large periods of time (weeks or months), and within each macro-period they divide time into a fixed number of *micro-periods* of variable length. The length of a micro-period is a decision variable that is directly related to the quantity produced in that period. The type of product that can be processed in that micro-period is defined by the set-up that was performed at the start of the micro-period. If the type of product does not change from one micro-period to the next, no setup needs to be performed.

The previous formulations do not explicitly add the shift/crew constraints because it would have greatly increased the number of variables, without adding much benefit to their formulation. In our case, however, they are useful, specially for the requirement of traceability, so we will define the macro-periods as an 8 hour shift and we will handle the increment in the number of variables by limiting the number of micro-periods within a shift to 3. By defining the size of the macro-period as the complete productive shift, we can easily add the shift/crew capacity constraints into the model and by forcing all production to start and finish during each shift, add the traceability constraint. We can also define the number of micro-periods to 3, because since the shortest setup takes at least 20 minutes, if more than 3 setups are done the efficiency of the line will be reduced below an acceptable level.

Amorim et al. [8] compare different models for lot sizing and scheduling, presenting the formulations by Kopanos et al. [62], Amorin et al. [9], Erdirik et al. [42] and Almada-lobo et al. [5], concluding that the formulation that achieved consistently the best computational performance was that of Kopanos et al. [62]. This formulation is interesting because it accounts for two types of setups: family and within family setups, which relates with the major and minor setups performed in wine bottling. Their approach has the problem that the major sequence dependent setups are related to changes between different family of products and the changes within a family are sequence-independent. In the case of wine bottling, the situation is exactly the opposite, since intra-family setup like color changes are sequence dependent while family changes, like bottle changes, take longer and are sequence-independent. Also none of these formulations take into account the crew/shift constraints.

Models for assigning limited resources for production scheduling, like production crews, have been proposed by Dastidar and Nagi [37]. They develop a MIP model for the scheduling of injection molding operations with multiple resource constraints and sequence dependent setup times and costs. In their formulation they block resources at work centers for production during the whole period, even if there is idle time, which is the case in the assignment of crews to the bottling lines. Almaeder and Almada-lobo [7] extend the GLSPPL model to account for scarce setup resources. They present a formulation that has better computational behavior than the GLSPPL of [76]. The problem with their formulation is that it is not easy to apply a decomposition approach as is the case of the GLSPPL.

Finally, the GLSPPL is well-accepted in the scientific literature and of high practical relevance [77]. Because of its flexibility, compared to [7], we will use it as our model base. To capture some critical aspects of the wine bottling, like crew/shift and sanitation constraints along with the cost of change in the number of crews, we will introduce variants in the formulation.

5.1.2 Solution methods

The GLSPPL is known to be a NP-Hard [40] problem. Zhu & Wilhelm [112] and Dastidar & Nagi [37] divide the methods for solving the lot sizing and scheduling models into optimizing and hybrid methods, and heuristic approaches.

The use of optimizing methods for scheduling and lot sizing for parallel machines, taking into account sequence dependent setups, is reduced and needs further development [8]. Clark et al. [31] and Stadtler [103] use optimization methods for single machine scheduling and lot sizing.

Amorim et al. [8] concludes that the formulation by Kopanos et al. [62] achieved consistent better computational results. Nevertheless, these formulations do not take into account the crew/shift constraints and also there would be needed a level of reformulation to capture the family sequence independence and intra-family sequence dependence setup times.

Since the addition of crew/shift constraints will inevitably increase the number of integer variable in the formulation of the problem and hence, reduce the solution performance through regular optimizing methods, a heuristic approach to solve the GLSPPL is necessary for solving large problems in a reasonable amount of time.

Toledo et al. [106] used Genetic Algorithms (GA) to solve the Synchronized and

Integrated Two-Level Lot Sizing and Scheduling Problem for a Brazilian soft drink company. Mohais et al. [80] and [78] uses GA for solving the lot-sizing and scheduling of large wineries with real world constraints. Unfortunately they do not indicate how the population or solution generation was made, so it is not possible to obtain any insights.

Given the characteristics of the problem we solving and the formulation we are using, it seems the best solution approach is to use a heuristic algorithm based on a decomposition method. This approach has been successfully used by Meyr et al. [77]. In his work he decomposes the parallel line problem into a single line problem, solving each line problem independently and then proceeding to integrate the solutions in an iterative process. We will take the approach of decomposing the problem by family of products and solving a SKU level problem for each family and then integrating the solution. This approach was mentioned by Meyr [77] as an extension of his work.

There is not a large body of research that uses the structural characteristics of the problem and incorporates them into their modeling and solution strategies. For the case of wine bottling the system has the particularity of having major setups when changing from one family of bottle to another and minor, sequence dependent setups, when changing from one color of wine to another. So [101] and Wittrock [108] are the first ones to introduce the concept of minor and major setups. Park et al. [88] and Li [65] developed heuristics that take into account the major/minor setups and uses this problem specific characteristic to their advantage. We will use this major and minor setup characteristic in the decomposition heuristic.

A decomposition heuristic approach will take advantage of the structure of the problem, dividing the solution process into two stages. This approach greatly reduces the complexity of the problem allowing us to solve real industry instances of over 6 lines, 200 SKUs and planning period of one month with 3 daily shifts. Because of the selected formulation of the problem, based upon [76], in a first stage, it is possible to aggregate the production by the family of glass or bottle and by doing so, reduce the size of the problem to an aggregated family model (FM). Once we have determined what family of products will be produced in which line and shift, we can then proceed to lot size and schedule each family independently. This problem corresponds to a family specific GLSPPL, much smaller in size with respect to the original, which can be solved with a regular optimization software.

5.2 Formulation of the lot sizing and scheduling optimization model for large wineries

We will proceed to describe the different components of the formulation for the lot sizing and scheduling optimization model for large wineries. We will first present the different parameters that govern the bottling planning process, next describing the different costs components of the objective function and finally, present the different parameters and constraints that govern the bottling process. We will finish comparing this formulation with the one proposed by Meyr [76].

5.2.1 Data requirements for planning a bottling schedule

Figure 47 shows the different groups of data parameters that interact in the process. The parameter information needed to perform the bottling plan can be cataloged into 5 different groups: demand, production capacity, sequence and compatibility, labor, and costs. The demand parameters corresponds to information related to the orders of the customers and inventory requirements of finished goods. The production capacity parameters relate to the capacity of each bottling line and the minimum number of cases. The sequence and compatibility parameters correspond to which SKU can be processed in which line, the color sequence dependent setup time and the changes in the family of glass. Labor parameters relate to the availability of crews per shift and the maximum number of crews that is possible to change from one day to the next. Finally, the last group of parameters correspond to the different costs.

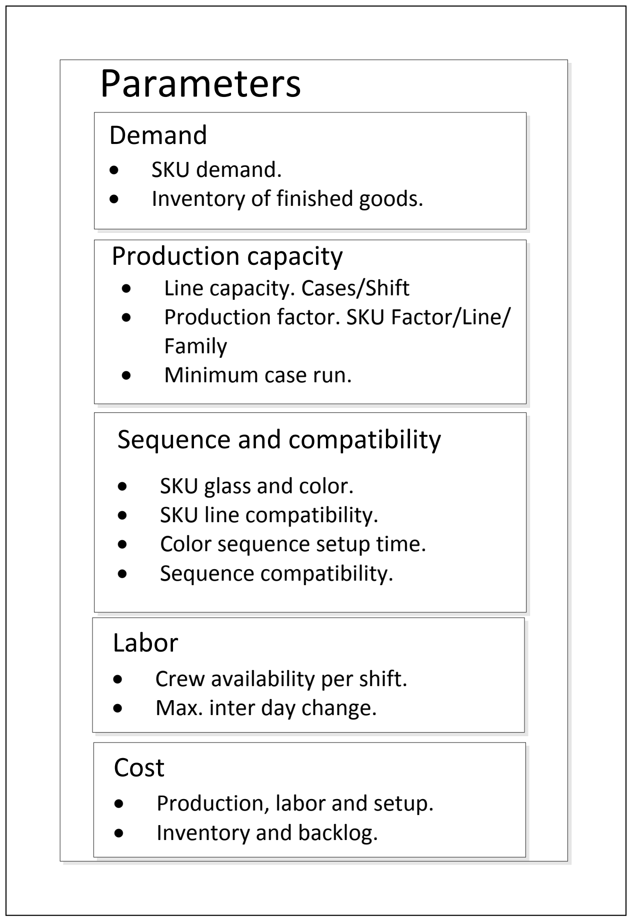


Figure 47: Model parameters.

The first aspect that needs to be defined in the bottling plan is the planning horizon. For the case of wine bottling, generally the production plan extends in a tactical level for a month, with weekly implementations, which are finally transformed into a daily production plan to be executed by each shift. In the case of large wineries, the daily production period is divided into three daily production shifts: day, night and swing.

The parameters are defined by the number of SKUs $j = 1, \ldots, J$ to be scheduled on $l = 1, \ldots, L$ parallel bottling lines. The finite planning horizon T consists of discrete macroperiods $t = 1, \ldots, T$ of a given length. For the case of the bottling lines, macroperiods will correspond to production shifts of 8 hours. For purposes of traceability and quality assurance, each bottling run must start and finish within the shift.

The original GLSPPL defines only one type of setup times for all the products. For the case of the wine bottling, we can take advantage of the structure of the problem and divide the setups into 2 groups: major family bottle setups, which take a whole shift to complete, and minor color and SKU setups, which can be done within a shift. This allows us to define a variation of the GLSPPL that we will call *General lot sizing and Scheduling Problem for Parallel Production with 2 Setup Types* (GLSPPL2). The production processes with 2 types of setup times can be found not only in bottling lines, but also in the printed circuit board industry, specifically in the testing of the boards. Testing a card is a very quick operation, lasting only seconds, but setting up a tester for a different family requires installing a different jig and different electrical connectors and takes up to an hour [108].

The major change of family $f = 1, \ldots, F$ is path independent and requires the line to stand down for a complete shift. The minor setups, that can be done within the shift, are path dependent and are defined by the color of the wine. For bottling purposes there are considered to be three colors of wine: red, white and pink. Changes in the color of the wine, within the same family of bottles, are dependent on the product that was previously bottled and can be completed within a shift. Setup times can range from 40 minutes for doing a change from a red or pink to a white wine, while the opposite change typically requires 20 minutes. Staying in the same wine color, but changing the SKU takes only 10 minutes because only labels and boxes must be changed.

If we compare, within a shift, the time taken for changing the color of the wine with the available productive time, each setup takes a considerable amount of productive time. For this reason, large wineries adopt the policy to have at most 2 changes of color within a shift. As an example of how the wine color setups affect the available productive time, if two major color changes are performed within a shift, this will take 80 minutes or 16.6% of productive time. If 3 color changes are performed, it will take 120 minutes or 25% of productive time. This policy of having at most 2 wine color changes, allow us to enumerate a finite color sequence $C_s\, s = 1, \ldots, S$, within the shift. The sequence corresponds to the time spent in setup time for a given change sequence and is defined by the color that was previously passed and up to two color changes within the shift.

The following parameter notation is used to formulate the problem:

<u>Parameters:</u>

Demand:

D_j demand for SKU j at the end of planning period. (Cases of wine)

I_{j0} initial inventory of SKU j at the beginning of the planning period (Cases)

Production capacity:

a_{jl} capacity consumption (time) needed to produce one unit of SKU j produced in line l (Minutes)

M_j capacity (time) per shift of line l (Minutes)

m_{jl} minimum lotsize of product j to be produced by shift (Cases)

u_{jl} maximum lotsize of product j to be produced by shift= $\arg\max\{D_j, m_{jl}, M_j a_{jl}\}$ (Bottles)

Sequence and compatibility:

TC_{sl} setup time of sequence $s \in S$ in line l (Minutes)

F_l SKU setup time in line l (Minutes)

K_l maximum number of SKU per shift in line l (Number of SKUs)

SC_{js} binary matrix that equals 1, if SKU j can be produced in sequence $s \in S$ (0 otherwise)

CO_{us} binary matrix that equals 1, if color sequence $s \in S$ can be produced after sequence $u \in S$ (0 otherwise)

GC_{jf} binary matrix that equals 1, if SKU j can be produced in line set up for family $f \in F$ (0 otherwise)

Labor:

R_t maximum number of crews to be assigned at shift t (Number of crews)

W^+ cost of increasing a crew between periods (Cost)

W^- cost of increasing a crew between periods (Cost)

Costs:

h_j inventory costs of finished product j (Cost)

c_{jl} production costs of product j in line l (Cost)

b_j backlog costs of product j in line l (Cost)

z_l setup costs in line l (Cost)

f_l fixed costs for using line l (Cost)

x_l fixed glass setup costs for line l (Cost)

If we compare our parameters with the ones used in [76] formulation, on a first look, our formulation has increased the number of integer variables by setting the macro-periods into intervals of only 8 hours, compared to the days or weeks in the original model. However, we took a step to reduce the number of integer variables by using the characteristics of the wine bottling constructing a new parameter TC_{sl} that takes the total setup time of a given sequence of products, since no more than 3 types (1 initial + 2 changes) of wine will be bottled during a macro-period (shift). Using a sequence of 3 wines significantly reduces the number of binary variables of the problem. Finally, to relate each sequence to the specific SKUs that can be bottled, we use a binary matrix that equals 1 if SKU j can be produced in sequence $s \in S$, and to determine if a wine color sequence $s \in S$ can be produced after sequence $u \in S$, we have a binary matrix that equals 1 if the sequence combination is feasible.

Another aspect of the problem is that the bottling lines are specific to certain sizes and types of bottles. For example, there are lines that will process only 750 milliliter bottles, while there are others that can process 750 milliliter bottles and also 1.5 liter bottles. Also, outside the regular glass bottle, there are different types of wine packaging, such as the bag in box, polyethylene bottles and laminated paperboard containers [94]. Each type of glass bottle and wine packaging corresponds to a different family of wine container. Table 28 shows on the first column the 10 lines that a large winery currently has and on the first line the 12 different families of wine containers that they use. The X symbolizes that is is feasible to bottle that specific container family in that line.

Table 28: Family line compatibility matrix.

	F-1	F-2	F-3	F-4	F-5	F-6	F-7	F-8	F-9	F-10	F-11	F-12	Fam.
L-1											X		1
L-2											X		1
L-3	X	X	X	X	X	X	X	X	X				9
L-4	X	X	X	X	X	X	X	X	X				9
L-5										X			1
L-6										X			1
L-7					X	X		X	X				4
L-8										X			1
L-9											X	X	2
L-10	X	X	X	X	X	X	X	X					8

Another parameter that has been added from [76] formulation is the maximum available number of crews. There is a limiting factor in the total number of crews available that can be assigned to each line and shift. Changing the number of active crews from one shift to another poses a cost for the company in terms of inactive workers, recruiting or layoff. Also crews are trained for certain certain types of lines and they are not fully flexible to be assigned to all types of line.

5.2.2 Lot sizing and scheduling decisions

The final goal of the bottling plan is to determine: which, when and how much to bottle at each production shift and decide on which SKUs and how much will be left unfilled for the next period. This will indirectly determine the moment and sequence of family and SKU setups, the moments in which the line will be down to perform sanitation, the level of finished good inventory and the assignment of crews to the specific lines, with their change in number from day to day.

The decision variables involved in scheduling and lot sizing of a large winery are:

Decision variables:

$P_{jlt} \in \mathbb{R}^+$ quantity (cases) of SKU j produced in line l during shift t.

$I_{jt} \in \mathbb{R}^+$ quantity (cases) of inventory of SKU j at the end of shift t.

$N_j \in \mathbb{R}^+$ quantity (cases) of SKU j backlog at the end of the planning horizon.

$K_{jlt} \in \{0,1\}$ equals 1, if SKU j is produced in line l during shift t (0 otherwise)

$C_{slt} \in \{0,1\}$ equals 1, if color sequence s is used in line l during shift t (0 otherwise)

$G_{lt} \in \{0,1\}$ equals 1, if bottle family setup is performed in line l during shift t (0 otherwise)

$A_{flt} \in \{0,1\}$ equals 1, if line is set for production of family f in line l during shift t (0 otherwise)

$\mathrm{MP}_t \in \mathbb{Z}^+$ number of crews available during shift t

$L_t^+ \in \mathbb{Z}^+$ number of crews added between shifts

$L_t^- \in \mathbb{Z}^+$ number of crews reduced between shifts

5.2.3 What makes an efficient bottling schedule

Figure 48 presents the different components of the objective function involved in the lot sizing and scheduling of wine bottling operations. The objective of a "good" bottling plan is to minimize the total cost and the amount of unfilled orders. The production costs are composed by production and inventory costs, while the cost of unfilled orders is related to the lost profit and damage to the commercial relation with the distributor/retailer.

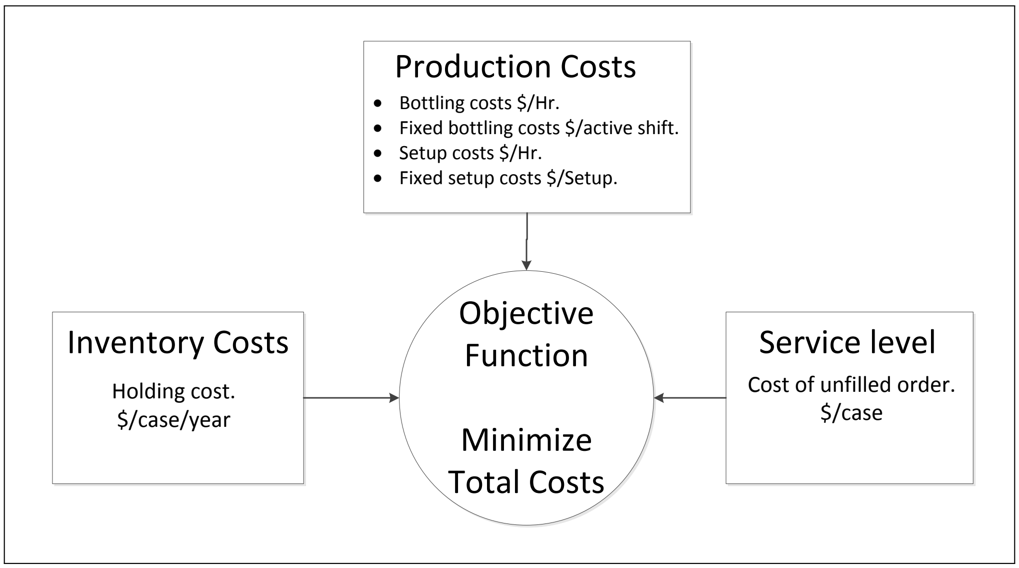


Figure 48: Components of the bottling lot sizing and scheduling objective function.

The formulation of the objective function is:

$$\min \underbrace{\sum_{j,t} h_j I_{jt}}_{\text{Holding costs}} + \underbrace{\sum_{j,l,t} c_{jl} P_{jlt}}_{\text{Production costs}} + \underbrace{\sum_{j} b_j N_j}_{\text{Backlog costs}}$$
$$+ \underbrace{\sum_{s,l,t} z_l \mathrm{TC}_{sl} C_{slt} + \sum_{j,l,t} F_l K_{jlt} + \sum_{l,t} x_l G_{lt}}_{\text{Setup costs}} + \underbrace{\sum_{t} (W^+ L_t^+ + W^- L_t^-)}_{\text{Crew change costs}}$$

Production costs are given by the hourly cost of the crew tending to the line, either performing setup or processing, the costs and plus fixed cost of having an active line (insurance, supervision, quality control, among some of the fixed costs). The costs vary according to the line type, because different crews sizes and capabilities are needed for each type of line, and also by the shift (day, night or swing). There is another labor cost, that generally has not received much attention, which corresponds to the cost related to changing the number of crews between one day and the next. As [79] points out: Excessive use of firing and hiring may be limited by union regulations and may create severe labor problems. Also crew turnover does have an impact on the unit level performance [59]. Finally, a stable workforce will allow the crew to gain productivity increments, because as they gain experience in the process they reduce the time required to perform the tasks. This phenomenon is know as: learning curve, experience curve, or learning by doing [11].

The objective of a bottling plan is to reduce the total inventory costs of finished product. Inventory is a key component in the equation, since bottles and packaging material can account for over 30% of the total costs of the final product [50] and the holding costs of inventories can range from 12% to 34% of the value of the final product[104].

The final component of the objective function is the service level, which corresponds to the cost of not fulfilling production orders at the end of the planning period and delay them to the next period. Generally the possibility of unfulfilled orders is not considered as an option in the planning process, because it is perceived to be so elevated, that the planner does not even consider this possibility in the planning process. Our model will consider the option of unfulfilled orders, by adding their cost in the model. The cost of leaving unfilled orders is correlated to the lost profit of the unfilled order plus a potential damage to the customer relation.

5.2.4 Constraints that govern the bottling process

Figure 49 shows the different constraints that govern the bottling plan. They can be grouped into: productive constraints, that corresponds to the demand, inventory and bottling line capacity restrictions; sequence and compatibility constraints, which make sure that a feasible sequence of SKUs is being bottled; sanitation constraints, which ensure that the line is at least sanitized every 7 days and finally, the labor constraints, which enforce the maximum number of crews are assigned to each shift.

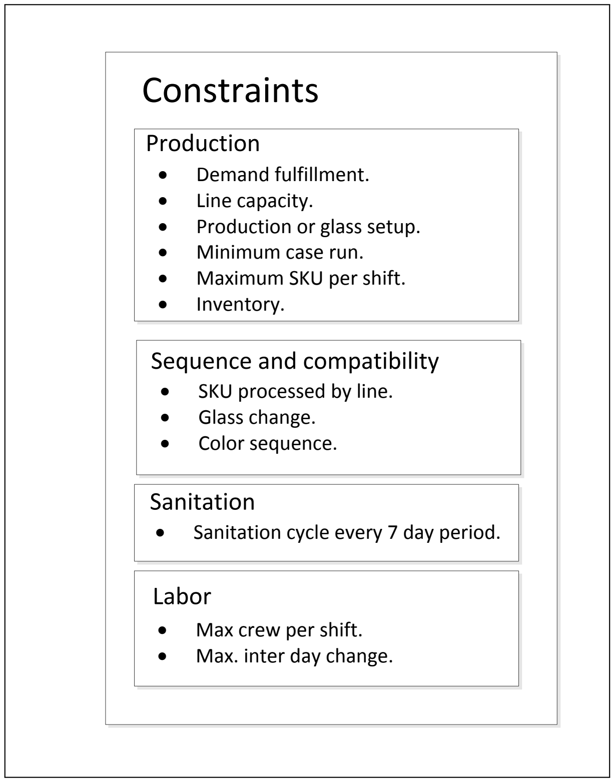


Figure 49: Parameters and constraints.

Constraint 4 insures that demand at the end of the period T is either served by production P_{ljT} or inventory from the previous period I_{jT-1}. If production or demand is not sufficient to supply the demand then an amount of production N_j is left unfilled. For the the produce-to-stock scheme the demand for each SKU is determined by a monthly forecast given by the marketing and sales departments. The accuracy of the forecast depends on the SKU, high volume-fast moving SKU have smaller errors in the forecast (3% to 5%) than low volume-slow-moving SKUs (10% to 20%). On average the forecast error can be in the order of 7% to 14%. Constraint 5 takes care of the inventory balancing.

$$D_j + N_j = I_{jT-1} + \sum_l P_{ljT} \qquad \forall j \in J \tag{4}$$

$$I_{jt} = I_{jt-1} + \sum_l P_{ljt} \qquad \forall \{t \neq \{T\} \in U, j \ \in J\} \tag{5}$$

The maximum capacity (M_l) of the line, represented by 6, is given by its production rate in terms of cases/shift which can be attained when the line is in full production of a single SKU. The capacity of the line is reduced because the crew is performing a sequence dependent wine color setup (C_{slt}) or a sequence independent setup as a label change (K_{jlt}). Having the flexibility to use 2 different setup times is an improvement from the formulation by [76].

$$\sum_j a_{lj} P_{ljt} \leq M_l - \sum_s \mathrm{TC}_{sl} C_{slt} - \sum_s F_l K_{jlt} \qquad \forall l \in L, t \in T \tag{6}$$

The setups of wine bottling lines can be characterized into two types: major setup, when the type of glass bottle is changed and minor setup, when anything else is changed.

A major setup requires large sections of the bottling line to be changed (bottle cleaners and fillers, closure mechanism, etc.) or calibrated (conveyors, elevation of bottle, pressure, etc.). This process takes a complete setup crew and a shift of 8 hours to be completed. Constraint 8 makes sure that only the SKUs of the glass type that the line has been set to are processed. Equation 7 enforces that the glass family is kept unchanged from one shift to the next or in the case of a change, a glass setup is made before a new family is bottled.

Minor setups can be performed during the production shift and can take from 20 minutes for a SKU change (K_{jlt}), which is a change in either the box, label or cork, to 60 minutes for a wine color change (C_{slt}), since a full cleaning and a flush of the system is needed before the new wine is passed. The number of these types of setup is limited to 2 within a shift. Only one sequence can be applied by shift 12, with a limited number of SKU changes 14. The compatibility of each sequence between shifts is enforced by 10 and the compatibility within a shift of each SKU with the color sequence is take care by 11.

$$P_{jl(t+1)} \leq u_{j,l}(\sum_{f \in F} \mathrm{GC}_{jf} A_{flt} + G_{lt}) \qquad \forall l \in L, j \in J, t \in T \neq \{T\} \tag{7}$$

$$P_{jlt} \leq \sum_{f \in F} u_{j,f} \mathrm{GC}_{jf} A_{flt} \qquad \forall l \in L, j \in P, t \in T \tag{8}$$

$$\sum_{s \in S} C_{slt} + G_{lt} \leq 1 \qquad \forall l \in L, t \in T \tag{9}$$

$$C_{sl(t+1)} + C_{ult} \leq 1 + \mathrm{CO}_{su} \qquad \forall s, u \in S, l \in L, t \in T \tag{10}$$

$$P_{ljt} \leq \sum_{s \in S} u_{jl} \mathrm{SC}_{js} C_{slt} \qquad \forall l \in L, j \in P, t \in T \tag{11}$$

$$\sum_{s} C_{slt} \leq 1 \qquad \forall l \in L, t \in T \tag{12}$$

$$K_{jlt} m_{jl} \leq P_{jlt} \leq u_{jl} K_{jlt} \qquad \forall l \in L, j \in P, t \in T \tag{13}$$

$$\sum_{j} K_{jlt} \leq E_l \qquad \forall l \in L, t \in T \tag{14}$$

The final constraint that needs to be taken into account when planning the bottle operations is the sanitation process. To avoid any contamination all lines need to be sanitized at least once every 7 days. This process takes a complete shift to be done and prevents a line from running with the same SKU for more than 7 days. It can be performed at the same time as a glass setup, so generally they are planned together to reduce the idle time.

$$\mathrm{MP}_{(t+3)} = \mathrm{MP}_t + L_t^+ + L_t^- \qquad \forall t \in T \neq \{T\} \tag{15}$$

$$\mathrm{MP}_t \leq R_t \qquad \forall t \in T \tag{16}$$

$$\sum_{s \in S, l} C_{slt} \leq \mathrm{MP}_t \qquad \forall t \in T \tag{17}$$

This formulation has a larger number of variables than the ones presented by Meyr

[77]. It adds detail into the formulation because new binary sequencing variables such as the glass setup, the active glass state, and the sequencing constraints are used. Meyr's model [77] uses only a binary setup state variable and a changeover variable. The detailed representation of setups, into major and minor, will allow us to decompose the model into two interrelated decisions: First, the decision of how to sequence the major family setup of products and second, within each family of products, perform an efficient scheduling of the shifts by selecting the adequate sequences of SKUs. The formulation also adds the workforce change, backlog and maximum number of SKU constraints, which takes the model closer to what the planner faces when scheduling the bottling lines of large wineries.

5.3 Adding robustness to the model

A valued aspect of a "good" plan is to remain feasible even after changes in the parameters (e.g., demand forecast inaccuracies, breakdown, capacity reductions, etc.). This is also called a "reliable" or "robust" solutions [13]. Unfortunately stability typically comes at the expense of sub-optimality. The objective is to determine the "best" sub-optimal solution that gives enough robustness to the plan to sustain feasibility under changes in the parameters.

Beyer and Sendhoff [17] indicate that the robust optimization approaches can be divided into two main classes: First, the methods which calculate the desired robustness measures $F(x)$ explicitly in the objective function and add related (robust) constraints and second, the probabilistic methods that treat uncertainties directly by optimizing noisy functions and constraints. We will use the first approach of integrating variability of some critical production planning parameters in the process of developing robust production planning systems. This multi-objective approach of has been used successfully by other researchers in such various areas as production planning, airline crewing and fleet planning [1, 2, 41, 66, 92].

The first step to construct a robust solution is to determine the sources of disruption to the production plan. Sabuncuoglu and Goren [97] indicate that the sources of disruption in the production schedules generally originate from: unexpected order arrivals, machine breakdowns, processing time variability, due-date changes, job cancellations, ready-time changes, rush orders and finally, scraps and waste. Another aspect that affects the quality of the plan, discussed by Clark [30], is the error in the demand forecast. From our conversations with the industry, they have indicated that the main sources of process variability are: First, unexpected order arrivals with an unreliable demand forecast and second, processing time variability in the setup and production, and third, bottling line breakdowns.

We will focus on the two sources of variability (demand and process) and device a mechanism in which they can be introduced into the model to produce robust solutions.

5.3.1 Demand driven robustness

A good plan schedules a percentage of the production at an early stage, so in the case that any customer demand unexpectedly appears, there will be product available to fulfill that customer requirement. This acts as a safety stock for the demand, which increases the stability of the production plan and reduces the need to reschedule [12, 102].

To add this characteristic to our model we will first define a parameter (SL) in terms of a percentage of the demand. This parameter represents the safety level that the inventory needs to reach, before a given period, so the demand can be "protected" from the unexpected arrival of orders. To avoid infeasibility of the model, we will introduce a variable SN_j that will add the flexibility to not produce the entire safety stock. In the objective function we will add a cost per case of not producing the required safety stock on time.

The changes on the model will be:

$$\min \quad \text{Original Objective} + \underbrace{\sum_{j} \mathrm{S}_j CS_j}_{\text{Unfulfilled safety stock}}$$

$$D_j\mathrm{SL} \leq I_{jP} - \mathrm{SN}_j \qquad \forall j \in J, P = S \in \{T\} \quad (18)$$

The cost of a sub-optimal solution is given by both the extra inventory costs generated by the safety stock that will be produced and the higher number of setups needed to be performed in order to produce the safety stock at an early stage.

5.3.2 Process driven robustness

A "good" bottling plan will look to utilize as much as possible the lines, minimizing the setup or idle times, and maximizing the usage of the available capacity. This solution is not robust and can easily become infeasible and possibly unrecoverable, because in the case that unexpected demand appears there will be no available capacity to fulfill this demand. A mechanism to add robustness to the model, from the process capacity standpoint, is to "optimally" introduce inefficiencies or idle times into the lines so there will be capacity available in the case of an unexpected event, such as breakages or rush orders.

One way to induce flexibility into the system is to reserve an amount of capacity that can be used just in case. This approach was initially proposed by Yellig and Mackulak [111] and adopted in revenue management by Akkan [3]. It was also implemented by Gupta and Wang [52] in scheduling of an outpatient clinic. To determine the optimal capacity hedge we will use the same approach as [111] and base the hedge capacity on the history of interrupted production or unplanned downtime of the bottling lines.

The implementation requires the addition of the following two constraints to the problem:

$$\sum_j a_{jl} P_{jlt} \leq M_l - \sum_s \mathrm{TC}_{sl} C_{slt} - \sum_s F_l K_{jlt} - \underbrace{U_{lt}}_{\text{Reserved capacity}} \quad \forall l \in L, t \in T \tag{19}$$

$$\sum_k M_l Y_l \leq \sum_k U_{l(t+k)} \forall l \in L, t \in \{0 \dots T - Z\}, k \in \{0 \dots Z\} \tag{20}$$

The capacity hedging in constraint is embedded in 19. In this constraint we will allow the model to decide how much and when to reserve that capacity over a determined period of time, given by a non-negative continuous variable U_{lt}. This corresponds to the amount of inefficiency that will be added to line l during period t. The objective is to achieve the desired reserved capacity level over a rolling period of time. Constraint 20 ensures that the amount of reserved capacity is given by a percentage of the available line capacity by the parameter Y_l, in the given rolling horizon of length Z. By allowing the reserve capacity to be allocated in a rolling horizon, we are not forcing inefficiencies into system in every period, but allowing the model to flexibly select the "optimal" moment to introduce them into the plan.

CHAPTER VI

DECOMPOSITION ALGORITHM FOR THE BOTTLING LOT SIZING AND SCHEDULING MODEL

The GLSPPL is an NP-Hard problem [40], making it a good candidate for the development and implementation of an optimization heuristic. Using the structure of the problem, we can device a decomposition heuristic that uses the fact that there are major and minor setups to decompose the problem into two interrelated problems. The first problem is to determine an optimal shift assignment and sequence of production at the aggregate family level, without taking into account the setups at the SKU level. With that optimal shift assignment at the family level, we can decompose the problem into a lot sizing and sequencing problem at each family individually, which greatly reduces the size of the problem.

Figure 50 presents a general framework of the computation. First it takes the aggregate production demand at the family level and optimizes a family aggregated model. The solution of this model gives us the shifts and sequences that will be assigned to each family as the glass setups. Since each family has been assigned different independent shifts, the problem can now be decomposed into a lot sizing and scheduling for each family, within the assigned shifts. This can be done independently for each family, obtaining the exact lot size and scheduling for each SKU.

Figure 51 shows the two stages of the heuristic. In the first stage, at the family level, we aggregated the demand and no special concern is given to the sequence dependent setups at the SKU level. At the second stage, when sequence dependent setup times are taken into account at the SKU level, the shift assignment may be insufficient to produce the required demand. The insufficient number of shifts will

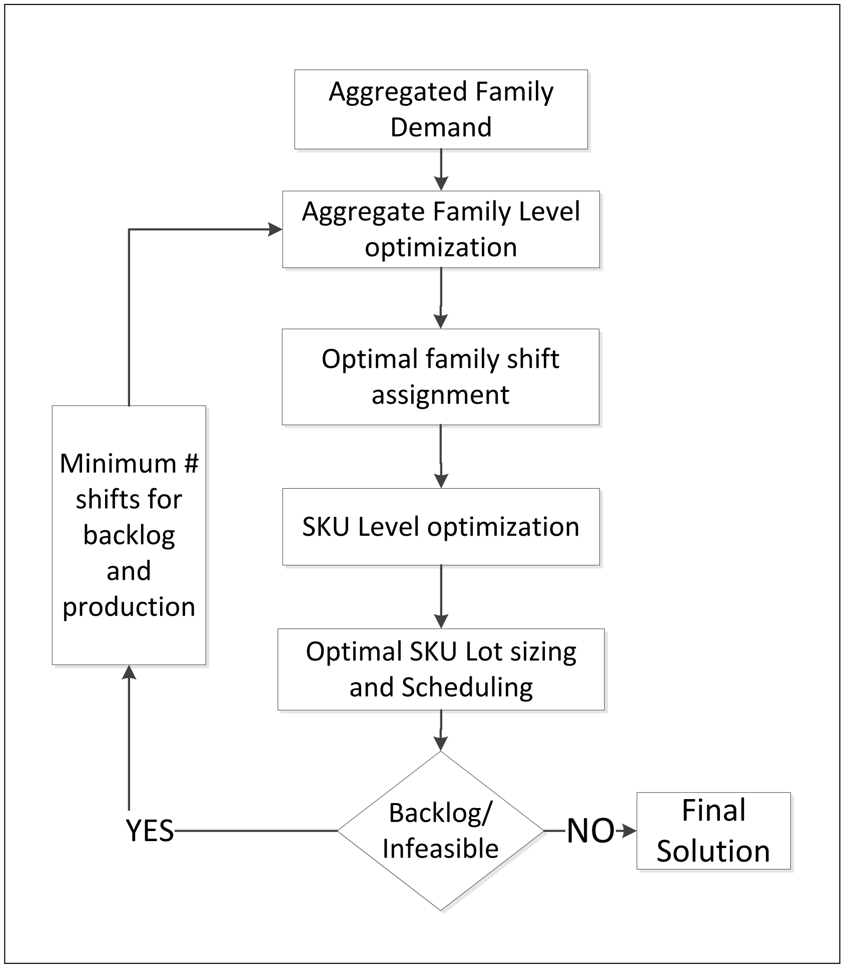


Figure 50: Decomposition computation framework.

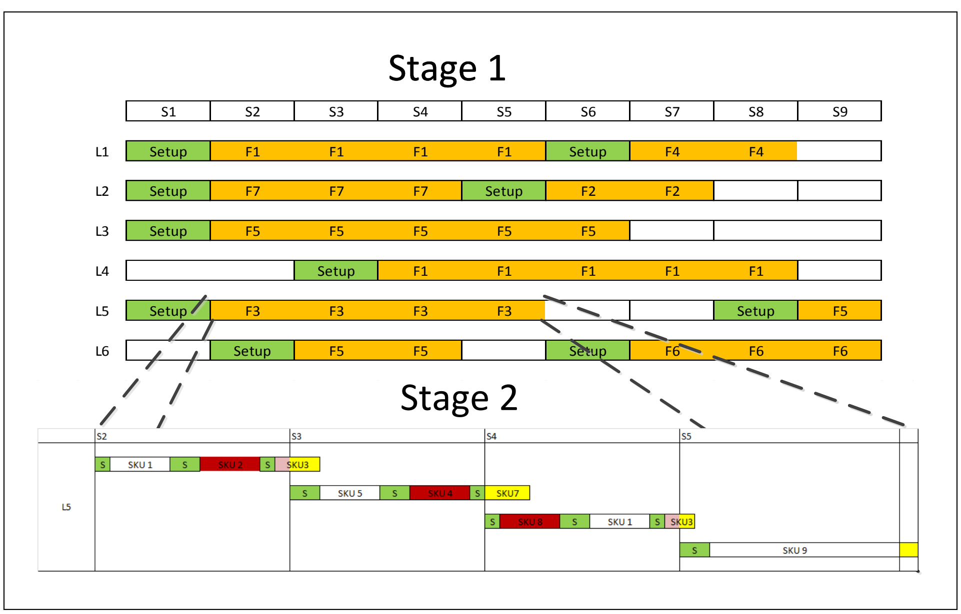


Figure 51: Two stage heuristic: family level model and SKU level model.

show up in the solution at the SKU level as over-scheduled lines. To fix the shift assignment at the SKU level, it is necessary to increase the number of productive hours to that family of products. By adding extra shifts to the current solution, we will have the required number of shifts to produce the demand. With this information we reiterate the model at the family level, with an added constraint on the minimum number of shifts required per family. The family model will give an assignment of shifts per family and glass setup scheme, taking into account the minimum shift constraint, and with this information we again optimize for each family at the SKU level. If no backlog is generated, we have an optimal lot sizing and scheduling; otherwise, we determine again the required shifts and repeat the process again until either no backlog is produced or the maximum number of iterations are achieved.

6.1 Decomposition of the GLSPPL problem: Family and SKU level models

We will now proceed to describe the models at the family level and SKU level, give a pseudo code for the algorithm and explain how we will introduce our robustness constraints into the algorithm.

6.1.1 Family level model

The family level model determines the optimal glass setup allocation and the family specific shift(s) assignment for an aggregated family demand. To determine an optimal assignment we first aggregate demand at the SKU level into a glass-family aggregated-demand given by D_f. This greatly reduce the size of the problem and its complexity since at the family level the setup times are sequence independent, so the SKU dimension is eliminated.

The family sequencing problem PM is:

Variables:

$P_{flt} \in \mathbb{R}^+$ quantity (cases) of Family f produced in line l during shift t.

$I_{ft} \in \mathbb{R}^+$ quantity (cases) of inventory of Family f at the end of shift t.

$N_f \in \mathbb{R}^+$ quantity (cases) of Family f backlog at the end of the planning horizon.

$G_{lt} \in \{0, 1\}$ takes 1, if bottle family setup is performed in line l during shift t (0 otherwise)

$A_{flt} \in \{0, 1\}$ takes 1, if line is set for production of family f in line l during shift t (0 otherwise)

$W_{flt} \in \{0, 1\}$ takes 1, if line l is active producing family f during shift t (0 otherwise)

$L_t^+ \in \mathbb{Z}^+$ number of crews added between periods t and $t + 1$

$L_t^- \in \mathbb{Z}^+$ number of crews reduced between periods t and $t + 1$

Parameters:

D_f demand of Family f at the end of planning period(cases)

h_f holding costs of Family f (per shift)

c_{fl} production costs of Family f (per unit) in line l

b_f backlog costs of Family j (per unit) in line l

f_l fixed costs for using line l (per shift)

x_l fixed glass setup costs for line l (per setup shift)

a_{fl} capacity consumption (time) needed to produce one case of family f produced in line l

MF_j capacity (time) per shift of line l (time) for family production.

CO_{fl} equals 1, if family f can be produced in line l (0 otherwise)

u_{fl} maximum lot-size of family f to be produced by shift (units).

$u_{fl} = \arg\max\{D_f, M_j a_{fl}\}$

I_{j0} initial inventory of Family f at the beginning of the planning period (cases)

R_t maximum number of crews to be assigned at shift t

W^+ cost of increasing a crew between periods

W^- cost of increasing a crew between periods

With this notation the family lot-sizing and sequencing problem can be formulated as:

$$\min \underbrace{\sum_{f,t} h_f I_{ft}}_{\text{Holding costs}} + \underbrace{\sum_{f,l,t} c_{fl} P_{flt}}_{\text{Production costs}} + \underbrace{\sum_{f} b_f N_f}_{\text{Backlog costs}} + \underbrace{\sum_{l,t} x_l G_{lt}}_{\text{Glass setup costs}} + \underbrace{\sum_{t} (W^+ L_t^+ + W^- L_t^-)}_{\text{Crew change costs}}$$

$$\text{s.t.} \qquad D_f + N_f = I_{fT-1} + \sum_{l} P_{flT} \qquad \forall f \in F \tag{21}$$

$$I_{ft} = I_{ft-1} + \sum_{l} P_{flt} \qquad \forall t \neq \{T\} \in U, f \in F \tag{22}$$

$$\sum_{f} a_{fl} P_{flt} \leq \mathrm{MF}_l \qquad \forall l \in L, t \in T \tag{23}$$

$$A_{fl(t+1)} \leq \sum_{f \in F} A_{flt} + G_{lt} \qquad \forall l \in L, f \in F, t \in T \neq \{T\} \tag{24}$$

$$\sum_{f \in F} A_{flt} \leq 1 \qquad \forall l \in L, t \in T \tag{25}$$

$$W_{flt} \leq A_{flt} \qquad \forall l \in L, f \in F, t \in T \tag{26}$$

$$m_{lj} W_{flt} \leq P_{flt} \leq D_f W_{flt} \qquad \forall l \in L, f \in F, t \in T \tag{27}$$

$$\sum_{f \in F} A_{flt} + G_{lt} \leq 1 \qquad \forall l \in L, t \in T \tag{28}$$

$$\sum_{f \in F, l} W_{fl(t+3)} = \sum_{f \in F, l} W_{flt} + L_t^+ + L_t^- \qquad \forall t \in T \neq \{T\} \tag{29}$$

Constraint 21 fulfills the demand or backlog from production or inventory at period T, while equation 22 enforces the inter temporal quantity balance. The maximum production capacity is enforced by equation 23. Constraints 24 to 29 are in charge of the glass family setup, so a family cannot be produced if either the line has been previously setup for that type of glass (G_{lt}) or the line is active on that family of glass (A_{flt}). Finally equation 29 reflects the labor crew changes from one shift to the next.

In the first iteration, the optimal number of shifts and glass setup required to produce the aggregated demand is determined by optimizing this model. Since the model does not take into account the sequence dependent setups at the SKU level, as indicated before, this solution might not be "optimal" at the SKU level. This will appear as backlog generated due to the lack of production shifts. To fix the required number of shifts on the next iterations, equation 30 will add a constraint that adjusts the number of active shifts to the amount required to avoid backlog at the SKU level. We will then re-optimize the family level model, with this added constraint that will add the required number of active shifts per family $\mathrm{AS}_f \in \mathbb{I}$. The added constraint is:

$$\sum_{l,t} W_{flt} \leq \sum_{l,t} W^{*}_{flt} + \mathrm{AS}_f \qquad \forall f \in F \quad (30)$$

To determine the number of shifts to increase per family in the next iteration, we will look for backlogs in the solutions at the SKU level. If one is found, it can be due to either a lack of available shifts to produce or to an optimal decision to not fulfill a certain number of orders. To determine which is the case, the next optimization will add production shifts to the families that require it. If those additional production shifts are not used and the same backlog is produced, it means that the backlog decision is not due to lack of production shifts.

6.1.2 SKU level model

As indicated before, the solution to the family level model will indicate the families of products that will be produced in the different shifts W_{flt} and also the shifts in which there will be a glass setup G_{lt}. Since each family will be produced independently on each shift, our problem can be decomposed into an independent optimization for each family to determine the optimal lot size and to determine the optimal sequence for each SKU that will be processed at each assigned shift. The optimal lot size and sequencing can be represented for each family of products as:

Variables:

$P_{jlt} \in \mathbb{R}^+$ quantity (cases) of SKU j produced in line l during shift t.

$I_{jt} \in \mathbb{R}^+$ quantity (cases) of inventory of SKU j at the end of shift t.

$N_j \in \mathbb{R}^+$ quantity (cases) of SKU j backlog at the end of the planning horizon.

$K_{jlt} \in \{0, 1\}$ takes 1, if SKU j is produced in line l during shift t (0 otherwise)

$C_{slt} \in \{0, 1\}$ takes 1, if color sequence s is used in line l during shift t (0 otherwise)

Parameters:

D_j demand of SKU j at the end of planning period (cases)

h_j holding costs of product j (per shift)

c_{jl} production costs of product j (per unit) in line l

b_j backlog costs of product j (per unit) in line l

z_l setup costs (per time) in line l

f_l fixed costs for using line l (per shift)

x_l fixed glass setup costs for line l (per setup shift)

a_{jl} capacity consumption (time) needed to produce one unit of SKU j produced in line l

M_j capacity (time) per shift of line l (time)

TC_{sl} setup time of sequence $s \in S$ in line l

F_l SKU setup time in line l

K_l maximum number of SKU per shift in line l

SC_{js} equals 1, if SKU j can be produced in sequence $s \in S$ (0 otherwise)

CO_{us} equals 1, if color sequence $s \in S$ can be produced after sequence $u \in S$ (0 otherwise)

GC_{jf} equals 1, if SKU j can be produced in line set up for family $f \in F$ (0 otherwise)

m_{jl} minimum lot-size of product j to be produced by shift (cases)

u_{jl} maximum lot-size of product j to be produced by shift (cases).

$u_{jl} = \arg\max\{D_j, m_{jl}, M_j a_{jl}\}$

E_l maximum number of SKU per shift in line l

I_{j0} initial inventory of SKU j at the beginning of the planning period (units)

R_t maximum number of crews to be assigned at shift t

W^+ cost of increasing a crew between periods

W^- cost of increasing a crew between periods

$$\min \underbrace{\sum_{j,t} h_j I_{jt}}_{\text{Holding costs}} + \underbrace{\sum_{j,l,t} c_{jl} P_{jlt}}_{\text{Production costs}} + \underbrace{\sum_{j} b_j N_j}_{\text{Backlog costs}} + \underbrace{\sum_{s,l,t} z_l TC_{sl} C_{slt} + \sum_{j,l,t} F_l K_{jlt}}_{\text{SKU setup costs}}$$

$$\text{s.t.} \qquad D_j + N_j = I_{jT-1} + \sum_l P_{ljT} \qquad \forall j \in J \tag{31}$$

$$I_{jt} = I_{jt-1} + \sum_l P_{ljt} \qquad \forall \{t \neq \{T\} \in U, j \ \in J\} \tag{32}$$

$$\sum_j a_{lj} P_{ljt} \leq M_l - \sum_s TC_{sl} C_{slt} - \sum_s F_l K_{jlt} \qquad \forall l \in L, t \in T \tag{33}$$

$$C_{sl(t+1)} + C_{ult} \leq 1 + CO_{su} \qquad \forall s, u \in S, l \in L, t \in T \tag{34}$$

$$P_{ljt} \leq \sum_{s \in S} u_{jl} SC_{js} C_{slt} \qquad \forall l \in L, j \in P, t \in T \tag{35}$$

$$\sum_s C_{slt} \leq 1 \qquad \forall l \in L, t \in T \tag{36}$$

$$K_{jlt} m_{jl} \leq P_{jlt} \leq u_{jl} K_{jlt} \qquad \forall l \in L, j \in P, t \in T \tag{37}$$

$$\sum_j K_{jlt} \leq E_l \qquad \forall l \in L, t \in T \tag{38}$$

$$K_{jlt} \in A_{Flt} \tag{39}$$

Constraints 31 and 32 require fulfillment of demand and backlog for the last period and the production inventory inter-temporal balance. Capacity and sequence dependent setup times are reflected in equation 35. Color sequence compatibility inter and intra-shift is determined by the equations 35 to 37. The maximum number of SKUs to be processed by shift is expressed in equation 38. Finally the most important constraint is 39 that states that a given SKU, at a certain shift can be produced in a line only if the family of that SKU is active on that line and shift, which is given by the family model. This constraint greatly reduces the solution space of the problem, since it reduces the available shifts to the ones that have been defined in the family level model.

By dividing the optimization process into two stages we greatly reduce the size and complexity of the problem. In the first stage the size is defined by the number of families and in the second stage, by the number of SKUs that belong to that family. This decomposition allows us to relax the constraint that relates the glass family with the SKU production, equation 35: $P_{jlt} \leq \sum_{f \in F} u_{j,f} \mathrm{SC}_{jf} A_{flt}$.

If a backlog is produced at the SKU level, even though the shift capacity is used to its maximum, the required number of extra shifts needed to produce that backlog can be computed by first multiplying the total backlog by the capacity consumption parameter, which gives us the total time required to produce the backlog. Next we divide this value by the length of the shift and take the ceiling to obtain the number of shifts required to produce the backlog. The equation to determine the number of additional shifts AS_f will be: $\mathrm{AS}_f = \lceil \frac{N_j a_{jl}}{SS} \rceil$

The algorithm pseudo code is as follows:

Algorithm 1: Pseudo code for optimization

```
Step 0. $r \longleftarrow 0$ ;
while run time < total-time-limit do
    Step 1. $r \longleftarrow r + 1$;
    if $r = 1$ (First run) then
        Step 2. Solve the family level model without Active Shift constraint;
        forall the $R \longleftarrow f \in F$ do
            Step 3. Solve the SKU level model for family $R$;
            if Optimal then
                Stop
            else
                $\mathrm{AS}_R \longleftarrow \left\lceil \frac{N_j a_{jl}}{SS} \right\rceil$ ;
                Go to Step 1;
            end
        end
    else
        Step 4. Solve the family level model with Active Shift constraint and
        $AS_R$ values;
        forall the $R \longleftarrow f \in F$ do
            Step 5. Solve the SKU level model for family $R$;
            if Optimal then
                Stop
            else
                $\mathrm{AS}_R \longleftarrow \left\lceil \frac{N_j a_{jl}}{SS} \right\rceil$ ;
                Go to Step 1;
            end
        end
    end
end
```

Since each problem at the SKU level is independent from each other, because each family of products has been assigned their own individual production shifts, we can take advantage of multicore or cluster computing and perform parallel optimization of each SKU problem. This allows us to run an optimization thread for each individual family, which greatly reduces the computing time required. We will compare the performance run time of the algorithm in both serial and parallel configurations.

6.2 Implementing robustness into the algorithm

To implement either the demand or the capacity robustness into the solution, some changes have to be made in the original implementation, so constraints can be integrated into the decomposition algorithm.

6.2.1 Demand robustness

To introduce the demand robustness into the solution we will only perform minor changes in the family and the SKU model. First, at the family model we will add the robustness in constraint 40, which forces the model to generate inventory by period P I_{fP}. The amount that needs to be produced is a percentage SL of the demand D_f, which can be considered as a safety stock to meet unexpected demand. To avoid infeasibility in case there is not enough capacity available to generate the specified safety stock, we add a variable SNF_f that reduces the required safety stock level at a cost of CSF_f.

At the SKU level, we replicate the procedure by adding a constraint 40, which forces the model to produce a safety stock before period S. Similarly to the family level, in order to avoid infeasible solutions we add a variable SN_j that reduces the required safety stock by period S, at a cost of CS_j.

The additional constraints for the family and SKU model are:

Family model:

$$\min \quad \text{Original Objective} + \underbrace{\sum_f SNF_f CSF_f}_{\text{Unfulfilled safety stock}}$$

$$D_f SL \leq I_{fP} - SNF_f \qquad \forall f \in F, P = S \in \{T\} \quad (40)$$

SKU model:

$$\min \quad \text{Original Objective} + \underbrace{\sum_j SN_j CS_j}_{\text{Unfulfilled safety stock}}$$

$$D_j SL \leq I_{jP} - SN_j \qquad \forall j \in J, P = S \in \{T\} \quad (41)$$

Both constraints will require the solution to produce a given level of safety stock by a certain period S or else a cost will be incurred.

6.2.2 Capacity robustness

Capacity robustness is introduced in the solution by reserving some idle capacity in a rolling horizon. This is done at the family level, in constraint 43, were we determine the optimal allocation of the spare capacity by reducing the capacity of the lines with a non-negative continuous variable U_{lt}. The optimal level of capacity to spare is set in constraint 43 by establishing a minimum percentage Y_l of the available line capacity to be set idle. The family level model is then solved and the resultant reserved capacity U_{lt} is passed to the SKU level model as a parameter. In constraint 44 we can observe that the new parameter U_{lt} reduces the available line capacity, so the required idle capacity can be achieved at this level.

Family model:

$$\sum_f a_{fl} P_{flt} \leq MF_l - \underbrace{U_{lt}}_{\text{Reserved capacity}} \qquad \forall l \in L, t \in T \tag{42}$$

$$\sum_{k, f \in F} M_l Y_l \leq \sum_k U_{l(t+k)} \qquad \forall l \in L, t \in \{0, \ldots, T-Z\}, k \in \{0, \ldots, Z\} \tag{43}$$

SKU model:

$$\sum_j a_{lj} P_{ljt} \leq M_l - \sum_s TC_{sl} C_{slt} - \sum_s F_l K_{jlt} - \underbrace{U_{lt}}_{\text{Reserved capacity}} \qquad \forall l \in L, t \in T \tag{44}$$

CHAPTER VII

MODEL IMPLEMENTATION AND COMPUTATIONAL RESULTS

Although cost is usually the most important performance indicator to quantify and compare the quality of the schedules generated by the different models, it is not the only one. Solutions that have similar total cost can differ significantly in the number of active shifts, the percentage of setup or idle time time or the amount of over-scheduled time. Also, adding robustness in the model produces sub-optimal solutions, so we need a mechanism that will allow us to compare the increment in total cost with the gain in robustness in the solution. In the first section we will present Key Performance Indicators (KPI) that will allow us to compare different solutions in multiple dimensions.

In the second section we will compare the computational results of the model and the heuristic. We will also analyze the benefits of using parallel computing on the solution speeds of the decomposition heuristic. Finally, to implement the solution in a winery we will present a computational tool to visualize and intervene the planned and optimized solutions.

7.1 Bottling schedule performance measures

A minimum cost schedule will generally delay production as close as possible to the demand date, to minimize the inventory costs, leaving little or no time to recover production in the case of a breakdown. It also maximizes the utilization of the line, so in the event of a rush order or a breakdown of the line, there is not much flexibility built into the schedule to insert that order or recover the lost production. In those cases production must be rescheduled.

Robustness is a desirable characteristic in a solution, but it comes with a sacrifice in the efficiency [16]. We need a mechanism for comparing the solution on these two dimensions, that can allow the decision maker to make a more informed choice on which solution to implement. Since the cost efficiency dimension does not fully capture the complexities involved in the planning process, we propose a two dimensional approach: efficiency and solution robustness. We will try to capture both dimensions in a set of KPIs that will give us the ability to analyze and compare different solutions.

The efficiency dimension can be characterized by the following KPIs:

- Costs: Set one plan as the baseline and compare the other plan costs. Also compare the cost components: holding, backlog, production and setup costs. The production costs are be divided into the fixed (line and active shift) and variable (direct labor costs an change in crew number). The setup costs are divided into the glass setup and the SKU/color setup costs.

- Active/Setup/Inactive shifts: Percentage of available shifts that are active or scheduled with production, setup in glass or inactive or not in use. This gives an idea of the utilization of the total available capacity.

- Setup: Percentage of the total active time spent in the glass and color setup.

- Idle time: Percentage of the total active time that the line is planned to be idle (not producing or in setup).

- Over-scheduled: Number of shifts that are over-scheduled and the percentage of active time that the shifts extends over the shift.

The robustness of each solution will be measured by the following KPIs:

- Percentage of SKUs below safety stock at target period: This number indicates the percentage of SKUs that do not have the desired safety stock to cover unexpected demand.

- Days required to achieve a level of safety stock: The optimal for this value is to be as close as possible to the target date.

- Number of periods below capacity robustness: The capacity robustness is determined by two parameters: the amount of required idle capacity and the rolling horizon in which that capacity should be available. If for some reason, for a given rolling horizon, the capacity robustness level is not met, the value of this indicator is incremented by 1 unit indicating that the robustness was not met during that interval. The optimal value for this indicator is 0, which states that capacity robustness has been achieved in all rolling horizon intervals.

- Average idle capacity per quarter: This value allows us to compare the distribution of the idle capacity between the different quarters.

- Standard deviation of idle capacity per quarter: This value allows us to compare how balanced is the distribution between the different quarters. We would prefer that this value was closer to 0, which indicates that capacity is evenly distributed among quarters.

- Absolute crew change: Changes in the number of crews from one period to the next. The better would be to have a stable crew, so the change would be as close as possible to 0.

These KPIs will allow us to compare different production plans.

7.2 Computational results

To compare the performance of the different models, we will use 12 different instances of bottling plans that were implemented by a large winery: 3 small instances of weekly plans ($S1{-}S3$), 3 medium size instances of 2 weeks ($M1{-}M3$) and 6 different monthly plan sets of instances ($PL1 - PL6$), based on real data from a large winery. Table 29 describes the different instances.

Information about the lines and their family compatibility was previously presented in table 28. This type of configuration is very typical for a large winery, since they have a very large number of different types of containers in which they bottle the wine. Some lines are specific to the type of product and some have flexibility to process a number of different families. We can observe that only a restricted set of SKUs can be bottled in lines 1, 2, 5, 6 and 8. This allows these families to be completely separated into line and family independent sub problems.

Table 29: Description of the test instances.

Instance	Days	# SKU	# Families	# Prod. Orders
S-1	5	59	9	169
S-2	5	54	9	169
S-3	5	46	8	132
M-1	14	90	10	299
M-2	14	127	11	353
M-3	14	99	9	316
L-1	30	189	11	655
L-2	28	195	11	646
L-3	28	208	11	687
L-4	30	172	11	652
L-5	31	195	11	603
L-6	29	204	11	540
L-7	31	167	11	445

Our small and medium instances are similar in size to those presented in the literature But our large instances have considerably more lines and SKUs. Meyr [76] used medium size instances composed by 8 periods with 2 lines and between 15 an 19 products, also Dastidar and Nagi [37] used up to 51 different products over a maximum of 45 molding machines over a maximum number of 30 periods; finally Ferreira et al. [44] used 23 different items over 2 machines in a maximum of 30 periods.

The models and algorithm were implemented using a personal computer with an Intel Core i7-3820 2.7 GHz, 8 GB RAM, using the Windows 7 operating system, compiled using x64 java 1.7r25. The models were solved using the optimization system GUROBI version 5.5 [83] with an optimality gap of 3%. Maximum execution time for full models was 53 minutes for small instances, 2 hours for medium size and finally, 4 hours for larger models. Unfortunately larger models were not able to be optimized to an acceptable gap. A maximum number of 4 iterations was set for the heuristic, with a maximum of 4 minutes to solve each family and SKU level model, with the same level of optimality gap.

7.2.1 Cost results

We will compare the total costs and the different cost components (holding, production, and setup) obtained by the full model and algorithm with the one that was implemented by a large winery for each instance. In Table 30 we can observe the relative average costs for each instance size, in the appendix in Table 36 are the complete tables with individual instances results. Compared to the base model the results achieve costs savings of 27.15%, 26.74% and 29.05% for the small, medium and large instances, respectively.

Figure 52 shows that the most significant cost savings originate from the reduction of the setup costs, with over 40% in cost reductions compared to the implemented. This cost reduction shows that the model can determine "better" bottling sequences than the planner since it is able to minimize the number of active shifts and the setup time required to produce the demand. The next significant savings comes from

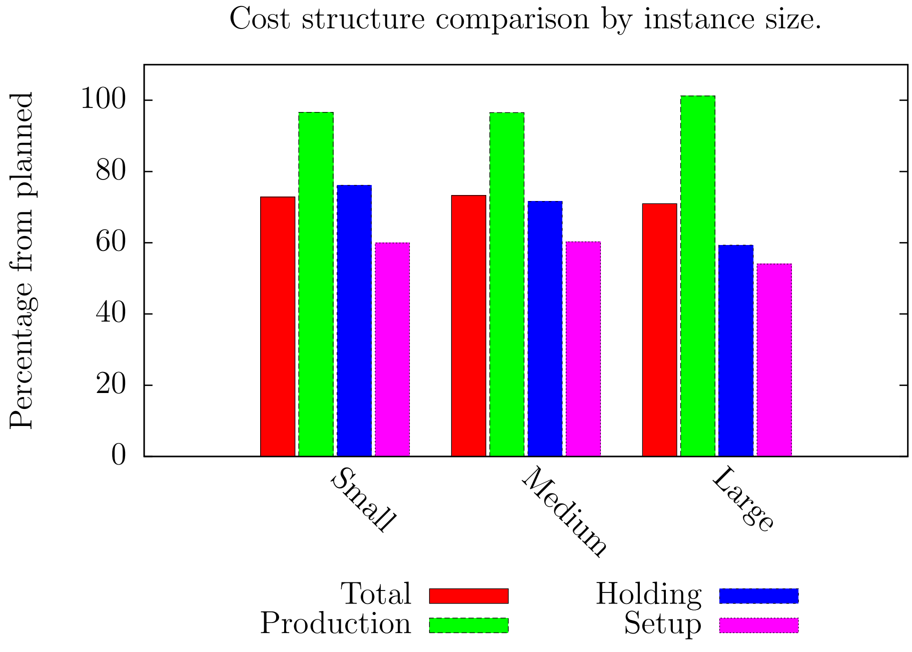


Figure 52: Cost structure comparison with implemented plan by instance size.

reductions in the holding cost, with cost being reduced over 30%. These reductions originate from optimally distributing bottling along the planning horizon, which results in lower finished goods inventory levels.

When applying the capacity and demand robustness constraints individually in figure 53, we can observe that the cost savings are reduced compared to the model. These reductions are called the "price of robustness" [16] and are due to the introduction of new constraints into the model that will allow the solution to remain feasible under unexpected changes in the parameters. If we observe the decomposition of the cost increment, we can observe that they come from different sources. When we applied the demand robustness constraints, the main increment in costs was in holding and setup costs. This is because the robustness constraints forces generating safety stock at an early stage, which involves a higher level of finished good inventories and setups. The introduction of a "reserved capacity", by the robustness constraints, forces the model to give a feasible plan with the same demand level but with less

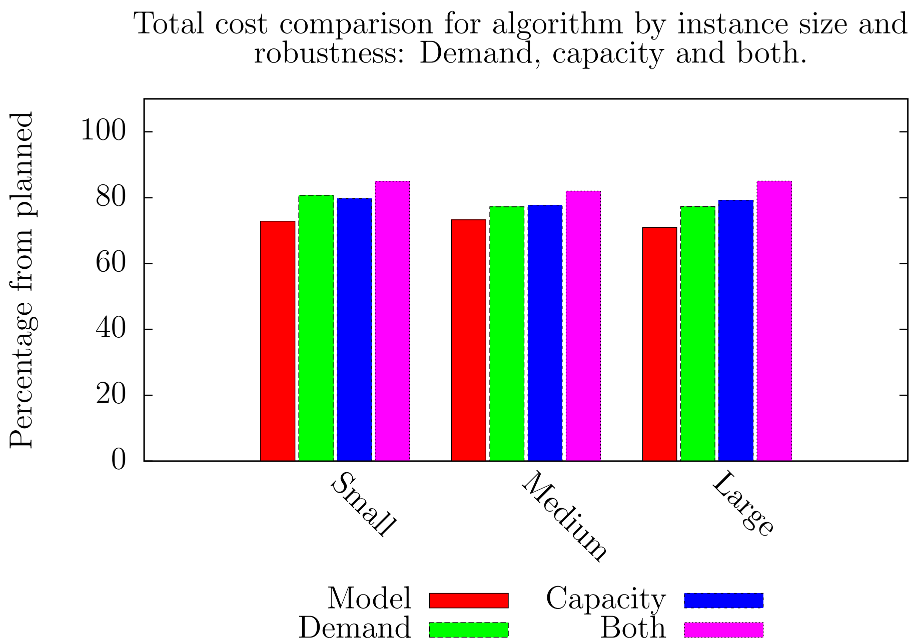


Figure 53: Total cost comparison with implemented plan by instance size and robustness.

available capacity. This produces higher setup costs because the demand can only be fulfilled by activating more productive shifts and performing more setups.

The reduction in the cost savings of applying the capacity and demand robustness constraints concurrently, is lower than the sum of the individual. If we look at the large instances, the sum of the demand and capacity robustness constraints individually applied is of 14.47 % while if applied concurrently produces a 14.07 % increment. This indicates that there are points of intersection or complementary interactions between both types of robustness.

When the company was asked if they would prefer to increase their total cost with the inclusion of the robustness in their planning, they indicated that they had previously thought that the cost of introducing the robustness would be much higher. As they pointed out: "its a small price to pay for the potential benefits that it could render".

7.2.2 Run time

Table 31 shows the run times for the full model and algorithm. For the full model in the small and medium size instance, the models stopped when they reached their running time limits with gaps of over 4% and 7% respectively. For large instances, no integer solution was found within the maximum running time. The large gaps and running times are due to the size of the problems, with thousands of integer variables.

The algorithm run times and optimality gaps were in acceptable levels with ranges from 6 minutes to 43 minutes. For large instances the model produced on average a solution with a gap of 1.93% in 9 minutes. When the capacity robustness constraints were introduced into the model the solution time increased to 43 minutes. We have faster running times if we compare our results with the run times obtained by Meyr and Mann [77]. They reported times of over 2 hours for large size problems with 7 production lines, 72 families of setup and a planning horizon of 12 months.

If we compare the sequential algorithm with the parallel algorithm (Table 32), the average run time improvements of the parallel algorithm are between 28.6% and 43.3%. The improvement is given by running each SKU level model on a parallel thread, so multiple SKU models can be optimized at the same time. It is interesting to notice that in two cases the running time of the parallel model was less than the sequential. This can be explained because in the sequential algorithm GUROBI uses a parallel branch and bound, so for these cases the parallel branch and bound was more efficient than running the models in parallel.

The model was executed in a 4 core 8 thread processor, and the number of families of glasses are over 10, so some threads had to be queued. The full potential of the algorithm could be achieved in a clustered computer with shared memory environment with as many cores as families.

7.2.3 Production parameters

Table 33 shows the average production parameters in terms of percentages of active shifts, setup time, idle time and over-scheduled time for the different size instances for the plan, full model and algorithm. The number of active shifts is reduced in 19% and 22% for the full model and 18% and 23% for the algorithm. These reductions in the number of active shifts originate, first, from a more efficient use of the lines by reducing the amount of idle time, and second, from a better schedule of the line that uses less time in either glass or SKU setups. This can be observed in a 19% or more reduction of the idle time and over a 2% reduction in the setup times. In almost all of the cases the over-scheduling of the lines were reduced.

If we look at the number of shifts and percentage of setup time and idle time, we can observe that the model and algorithm generates a better allocation of production along the planning periods. This is finally reflected on the fact that the main cost savings comes from reductions in the holding and setup costs.

The inclusion of robustness has not increased the number of shifts and in some cases it even reduced them. This is because the model reallocates the production to fulfill the required safety stock or idle capacity, without the need of new shifts. This production reallocation is also reflected in the increase in the setup times for the robust model.

Table 30: Relative average total, production, holding and setup cost for each instance size.

Instance	Cost	Planned	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S	Total	100.00%	74.54%	82.50%	77.22%	82.65%	72.85%	80.70%	79.75%	85.01%
	Production	100.00%	96.39%	96.66%	96.66%	96.79%	96.61%	96.95%	95.18%	95.43%
	Holding	100.00%	75.51%	81.65%	75.06%	80.37%	76.13%	75.99%	76.72%	79.76%
	Setup	100.00%	63.64%	77.49%	68.67%	78.33%	59.93%	75.04%	75.25%	84.23%
M	Total	100.00%	76.57%	84.47%	76.64%	86.36%	73.26%	77.24%	77.72%	81.99%
	Production	100.00%	97.95%	99.27%	98.77%	99.41%	96.52%	98.35%	97.95%	97.52%
	Holding	100.00%	69.60%	73.88%	67.09%	78.19%	71.56%	65.50%	60.92%	68.53%
	Setup	100.00%	69.45%	85.51%	70.90%	86.76%	60.24%	74.25%	79.69%	83.12%
L	Total	100.00%	-	-	-	-	70.95%	77.16%	79.21%	85.02%
	Production	100.00%	-	-	-	-	101.22%	100.51%	100.96%	99.91%
	Holding	100.00%	-	-	-	-	59.32%	63.85%	55.88%	64.24%
	Setup	100.00%	-	-	-	-	54.00%	67.76%	80.12%	86.97%

Table 31: Average run time and optimal gap by instance size.

Instance	Parameter	Full Model				Parallel Algorithm			
		Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S	Time (sec.)	3200	3200	3200	3200	337	655	850	887
	gap (%) *	4.19%	4.73%	4.53%	4.40%	1.73%	1.87%	1.87%	1.47%
M	Time (sec.)	7200	7200	7200	7200	380	692	495	1196
	gap (%) *	7.01%	10.70%	7.05%	18.88%	2.45%	3.72%	2.50%	2.34%
L	Time (sec.)	-	-	-	-	534	831	2567	2567
	gap (%) *	-	-	-	-	1.93%	2.17%	2.79%	2.01%

Table 32: Run time improvement for parallel algorithm versus sequential.

Instance	Run Time Improvement			
	Model F	Model D	Model C	Model B
L1	55.1%	5.1%	0.4%	44.5%
L2	60.4%	-3.6%	57.0%	37.9%
L3	58.4%	22.4%	56.3%	39.9%
L4	25.8%	43.7%	48.8%	30.7%
L5	51.7%	31.4%	5.0%	43.9%
L6	57.2%	79.9%	46.2%	40.6%
L7	-5.7%	21.2%	56.3%	16.0%
Average	43.3%	28.6%	38.6%	36.2%

Table 33: Average production parameters by instance size.

Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S	Shifts	100.00%	81.00%	81.00%	82%	82.00%	82.00%	81.00%	77.00%	78.00%
	% Setup Time	17.33%	13.15%	16.08%	14.02%	15.86%	11.78%	15.32%	16.90%	17.88%
	% Idle Time	25.71%	10.41%	10.45%	11.32%	10.60%	11.30%	10.64%	6.93%	7.00%
	% Over Time	2.02%	0.14%	0.22%	0.10%	0.25%	0.01%	1.17%	0.34%	0.02%
M	Shifts	100.00%	78.00%	80.00%	79.00%	80.00%	77.00%	76.00%	75.00%	77.00%
	% Setup Time	13.82%	12.48%	14.97%	12.92%	15.13%	10.84%	14.30%	15.76%	15.38%
	% Idle Time	27.58%	8.61%	8.59%	8.68%	8.96%	8.88%	7.95%	8.49%	8.97%
	% Over Time	1.98%	0.33%	0.34%	0.18%	0.37%	0.01%	2.87%	3.18%	0.92%
l	Shifts	100.00%	-	-	-	-	83.00%	84.00%	81%	83.00%
	% Setup Time	14.37%	-	-	-	-	8.32%	10.69%	14.69%	15.16%
	% Idle Time	22.76%	-	-	-	-	5.42%	6.47%	5.59%	6.49%
	% Over Time	1.67%	-	-	-	-	0.06%	0.07%	1.68%	0.08%

Looking at the production parameters we can determine that the solutions given by all of the variations of the models have better production parameters than the original plan. The only exception is the algorithm in the medium size instance, in which the over-scheduling of the line is higher than the plan, which can produce "unstable" solutions that can become infeasible.

7.2.4 Demand robustness

Table 34 shows the results for the two demand robustness parameters. As expected, the full model reduces the solution robustness for the medium and large size instances, increasing the percentage of SKUs below safety stock.

Applying the demand robustness constraint significantly reduces the percentage of SKUs below safety stock, from 67.77%, for the original plan, to 54.96 %. By reducing the percentage of SKUs below the safety stock we handle the sudden appearance of unexpected demand, without needing to reschedule production. The model that contains both robustness reduces the number of SKU below safety stock to almost the same level as one that only enforces the demand robustness.

For large instances there is a small difference between the original plan and the different models in the days required for the 85% of SKUs to reach the safety stock. This small difference has two explanations: First, the original plan already incorporates the demand robustness because the planner accounts for the possibility of unexpected demand. The second explanation is that the mechanism in which we introduced demand robustness into the model is binary, so if the model is unable to completely fulfill the safety stock by the target date, the model has no incentive to do it partially.

7.2.5 Capacity robustness

Table 35 shows the average capacity robustness parameters for each instance size. We can observe that the original plan already had capacity robustness embedded into the plan, since the average number of periods below the capacity robustness level is 0 for all instances. The problem of the original plan is that robustness is obtained through a high level of idle time on every quarter, which reduces the efficiency of the line.

If we observe the full model solution, the optimization reduced the idle time of the line and the change in the number of crews, but it also reduced the capacity robustness of the plan with 5.71 periods below capacity robustness. When we impose the robustness constraints, the number of periods below capacity robustness is set to 0. It would be expected that the idle time would increase for the robust model, but it remained stable. An explanation for this behavior is that the robust model uses the same amount of idle time as the optimal model, but efficiently spreads it along the periods to fulfill the robustness requirements.

Finally, applying capacity robustness reduced the variability in the number of active crews. So the robust solution will have available capacity and also have a stable number of production crews. Two highly desirable characteristics in a large winery bottling plan. Stable crews can benefit from the learning curve effect and having available capacity helps handle the appearance of unexpected customers orders, without much alteration of the original plan.

Table 34: Average demand robustness parameters by instance size.

Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S	% SKU below SS	51.32	43.83	3.85	43.14	0.56	42.82	10.02	46.79	10.97
	Days for 85%	3.33	2.67	1.67	3.00	1.67	2.67	1.67	3.00	1.67
M	% SKU below SS	52.11	58.64	6.48	60.65	36.45	52.62	35.98	61.50	16.20
	Days for 85%	9.00	8.67	3.33	8.67	5.00	8.33	7.00	8.67	4.00
L	% SKU below SS	67.77	-	-	-	-	83.89	54.96	91.08	53.19
	Days for 85%	19.86	-	-	-	-	19.57	19.29	19.86	18.43

Table 35: Average capacity robustness parameters by instance size.

Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S	Ave. # periods below CR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Ave. Idle per quarter	100.0%	33.9%	33.5%	36.9%	34.0%	36.8%	34.0%	21.1%	21.2%
	Est. Dev. Idle per quart	100.0%	71.1%	88.4%	87.7%	98.9%	58.0%	60.9%	55.8%	1.4%
	Abs.Crew Change	100.0%	113.1%	131.4%	89.3%	112.7%	142.0%	193.7%	62.0%	46.5%
M	Ave. # periods below CR	0.00	2.00	0.33	0.00	0.00	0.66	0.00	0.00	0.00
	Ave. Idle per quarter	100.0%	24.5%	25.0%	25.0%	25.9%	24.9%	21.8%	23.3%	25.1%
	Est. Dev. Idle per quart	100.0%	33.9%	65.8%	52.8%	67.8%	60.3%	57.5%	62.2%	0.5%
	Abs.Crew Change	100.0%	108.3%	104.0%	109.3%	101.5%	87.0%	98.7%	102.7%	79.3%
L	Ave. # periods below CR	0.00	-	-	-	-	5.71	3.71	0.00	0.00
	Ave. Idle per quarter	100.0%	-	-	-	-	22.3%	28.9%	21.6%	27.3%
	Est. Dev. Idle per quart	100.0%	-	-	-	-	61.2%	70.7%	99.5%	0.5%
	Abs.Crew Change	100.0%	-	-	-	-	75.0%	78.9%	69.6%	71.7%

7.3 Visualization module

The bottling planning process is a challenging task that requires the integration of a large number of sources of information within the organization. For example, demand and inventory levels are given by marketing and sales, production parameters such as the setup times and productivity of the lines are given by operations, and availability of productive crews is given by human resources. Production planning needs to integrate all of them to produce a feasible and efficient bottling plan that will coordinate the purchase of bottling materials, the transport of wine, the hiring/firing of production crews, and the preventive maintenance and sanitation of the bottling lines.

The large number of variables and parameters that interact in the process and the lack of specialized software or tools to support the planning and scheduling of the bottling lines, presents us an opportunity to develop a computational planning visualization tool that will help the decision maker to generate better and more robust bottling plans in less time.

From our interaction with the industry we have been able to conceptualize a decision support system than will help in the planning of the bottling lines for large wineries. Figure 54 shows the different modules that compose the system. The first module enables the user to import the schedules already produced as spreadsheets by the planner. This feeds the demand module, which gives the planner the opportunity to make changes in the demand quantity and products. The parameter module allows the planner to introduce all the cost, labor, and specific line production parameters. The planner can enter a large number of demand or parameter scenarios, which he or she can combine to analyze the effect of different situations. Finally, the setup module allows the planner to modify the different SKUs setup times.

Once all the demand, parameter, and setup information are in the system, the planner can access the optimization module. The planner is asked to select the desired

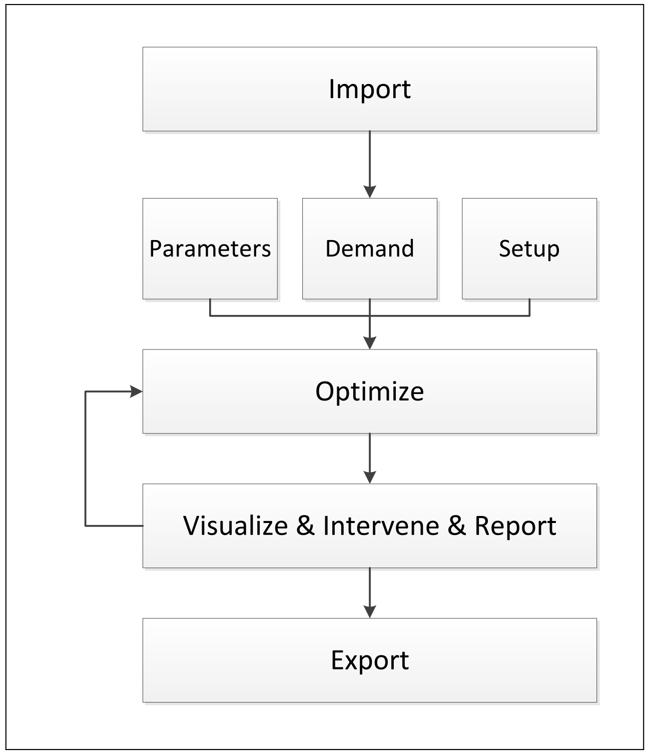


Figure 54: Planning and visualization module structure.

demand profile, parameter scenario, and setup times to be used in the optimization. It also gives him or her the ability to set optimization and robustness parameters, such as: running time, optimal gap, import previous glass setups, enforce sanitation, and set the safety inventory parameters and the reserve capacity parameters.

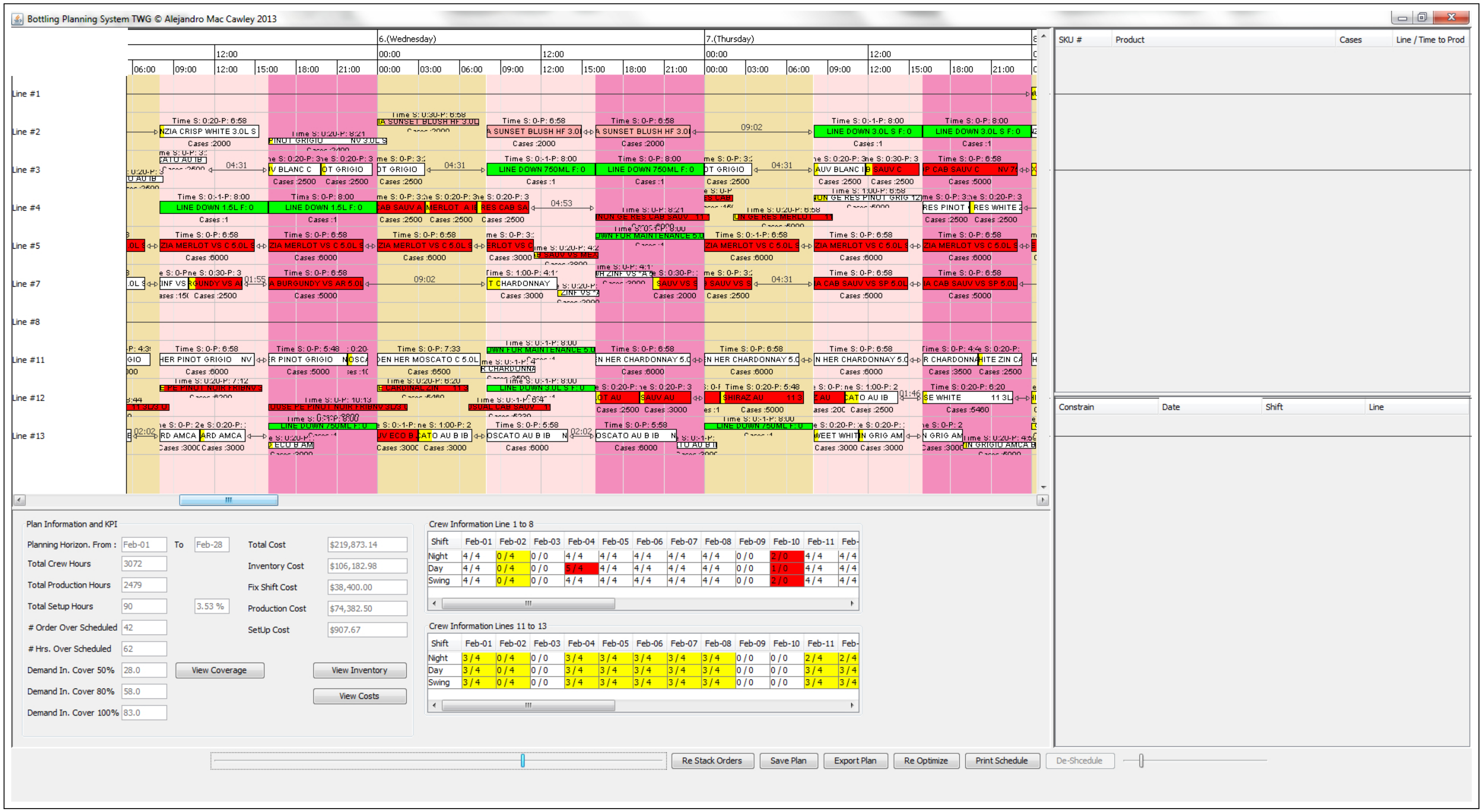


Figure 55: Visualization system screen shot.

Once the optimization process has finished, the solution is presented in the visualization module with other KPIs. Figure 55 presents a screen shot of the visualization and intervention module. It is divided into four different panels that display information for planning purposes. The main panel contains a Gantt chart that represents each production line and the production schedule for each shift, setup, and production. Colors represent the different type of wine (red, pink and white) and the planner can edit the solution by drag and drop, or by using a pull down menu. Information of each production order is presented when the mouse is hovered over its representation. The bottom panel shows the information regarding the costs and the different crewing information and KPIs of the plan. The table in the upper left shows all the backlogged orders.

The planner has the option to re-optimize the plan, along with all the fixed orders and setup constraints that he or she has built in. The system will run the optimization again adding all of the constraints that the planner has introduced and present the new solution. The planner can again edit the solution and if needed, re-optimize once more. This iterating procedure allows him or her to change the solutions and parameters many times, until the planner is satisfied with the production plan.

CHAPTER VIII

GENERAL CONCLUSION AND FURTHER RESEARCH

For shipments of wines coming from the southern to the northern hemisphere in non-refrigerated containers to the US we can conclude that Robert Parker was right in one sense: a significant percentage of the shipments of wine have been likely exposed to temperatures of 30 or more degrees Celsius for a significant amount of time. The likelihood of exposure to extreme temperatures is dependent on the phase of transport, route and the season of the year in which the shipment is done. Furthermore the cumulative change in the chemical reactions in the product can be modeled based on the Arrhenius equation. With this information we can compare the rate of change at the shipping temperature with that which would happen at ideal controlled storage temperatures of 13 °C. Results indicate that on average the shipments coming from the southern hemisphere to the northern hemisphere have advanced their natural chemical development by in 76% due to the temperature exposure.

Analyzing the different transport phases, results suggest that the phases of highest temperature danger are: the transshipment phase during the months of December to March and the destination port to importer phase during the June to September period. On the other side, the phase that has the smallest temperature danger is the winery to port phase during the months of June to September.

We have collected the largest database of shipping and temperature history and have devoted much of this thesis to mining that data. This has allowed us to produce some general recommendations to reduce the likelihood of extreme temperature exposure during wine shipping in dry containers from southern to northern hemisphere. First, avoid transshipment phase; second, avoid high temperatures in the northern hemisphere by shipping in Oct-May; third, if you must ship during the June-September ship and move the container fast and fourth, if you have a choice, ship to the West coast of the US.

The thermal liner is effective in producing an external-internal temperature differential, with an average temperature differential, for external temperatures above 40 °C of 5 °C. Also the liner is effective in reducing the daily temperature ranges, for example, when external temperature daily range has been of 20 °C the internal range been only 5 °C.

Finally, we developed a device that is able to simulate the temperatures to which the wine has been subjected during transport, so we can isolate and analyze the temperature effect in the perceived quality of the product. We performed blind tastings with purchasers at the consumer end of the supply chain. The results of the blind tastings indicate that the effect of temperature depends on the type of wine (red or white) and the quality of the product. For white wines the judges were able to detect the differences in the wines that were subjected to shipping temperatures and preferred them, indicating that the wines that had been subjected to shipping temperatures have improved. For the case of red wines, the judges were unable to detect the differences on the glasses and the preference towards the wines were mixed, so we cannot indicate any conclusion either favorable or unfavorable on this group. Further research needs to be done to determine the effect of aging (over 5 years) on the quality of the product.

On the second part of this research we solved in reasonable time-frame the bottling lot sizing and scheduling problem of a large winery. This has been achieved by first, developing a new formulation of the General Lot Sizing and Scheduling Problem for Parallel production Lines (GLSPPL) with sequence dependent setup time that takes into account the particularities of the bottling problem. Second, by proposing a decomposition algorithm that produces good solutions within a reasonable time-frame.

The proposed formulation closely resembles the problem that large wineries are confronted when lot sizing and scheduling their bottling lines. It incorporates aspects such as: minor sequence dependent set-up times, major bottle set-up that are not sequence dependent, labor, traceability and finally, sanitation constraints. Adding these constraints allows the model to produce solutions that are closer to what the bottling decision maker would implement, reducing the need to intervene the proposed solution. We observed on average, total cost reductions of 27% for large instances for the model produced solution when compared with the implemented bottling plans. The cost reductions originate from reductions in the required set-up times and by reducing the inventory levels. The model has been validated with two large wineries and is currently being implemented in one.

The proposed solution method uses structure of the problem by taking advantage of the existence of major and minor set-ups, decomposing the solution process in a two step iteration process. The first step optimizes the lot-size and sequence at an aggregate family level performing an assignment of the shifts and in a second stage, we optimize, using the previous shift family assignment, an SKU level lot sizing and scheduling problem with sequence dependent setup times. This solution method was tested in real life size instances and compared with the full monolithic model.

The computational test indicate that for real size instances, the decomposition approach produces solutions, with an acceptable optimal gap, in running times that range from 300 to 600 seconds. This running times can be reduced significantly if the algorithm is executed in parallel on multi-threaded computers, reductions of 5% to 60% have been reported for the parallel execution.

Finally, we present two mechanism to add demand and capacity robustness into the model. This is done by adding constraints that forces the model to produce a percentage of the demand at an early stage and also keep some production capacity idle in a rolling horizon. The addition of these constraints did not add significant running time into the model and could be solved with an acceptable optimal gap. The introduction of the robustness constraints produced an increment of 3% to 12% in the total costs. When the solutions were presented to the decision makers, they indicated that the benefit obtained by adding robustness outperformed the cost increment and they would implement the proposed robustness in their production process.

8.1 Lessons and recommendations for international logistics of temperature sensitive products

First, any product that is transported from the Southern to the Northern hemisphere in non-refrigerated container is very likely to be exposed to dangerous temperatures, specially high temperatures, independently of the season in which the transport is done. If the quality of the product is affected by the exposure to heat, it is recommended to use refrigerated containers. Second, there are certain phases during transport that have higher danger of exposure to extreme temperatures, particularly the the transshipment phase and the destination-port-to-importer phase during summer. To reduce temperature danger, transshipment should be avoided and during the summer the container should be moved as quickly as possible from the destination port to the importer. Third, shipments from the Southern to the Northern hemisphere should be done during the Northern hemisphere winter to reduce the danger of extreme temperature.

The liner is effective in keeping temperatures stable inside the container. It effectively reduces the thermal conductivity allowing a differential of temperature between the interior and exterior of the container. It also buffers the daily temperature range. So if during the transport we expect that the cargo will be exposed to strong daily temperature variations, the use of the liner is recommended. If we expect stable temperatures (either high or low) the thermal liner will not be so effective, since internal and external temperatures will equalize.

Our data suggests that in the case of white wines the consumer is able to detect the differences in the wines and when asked for preferences, he shows a predilection towards the wines that have been exposed to shipping temperatures. For the case of red wines, the consumer is unable to detect whether the wine has been exposed to dangerous temperatures. This suggest that for such wines the main temperature risk during transportation is of cork displacement.

8.2 Further Research

A rich area of further research is how the quality of a product is affected by the processes along the supply chain. It seems natural to begin by documenting the environmental conditions to which the products are subjected during their flow in international supply chains. Environmental conditions such as temperature, vibration, humidity and light that can affect the quality of the product. Once the risk has been quantified, the shipping conditions can be simulated under controlled conditions to determine the effect in the quality of the product. As advancement in this area we mention the work by Manzini and Accorsi [71] who have performed studies in the shipment of olive oil and the effect of vibration in the quality of the product.

APPENDIX A

SHIPPING TEMPERATURES AND TASTING APPENDIX

A.1 Documenting historical temperatures

To track the temperature from the origin to the destination, we used a temperature recording device called Thermocron DS1921G iButton [73] manufactured by Maxim. The device has the capability to record up to 2048 temperature readings at preset intervals. The recording intervals were set to 2 hours, which gave us enough granularity to capture the daily temperature variations and also allowed us to capture data for extended period of time, 170 days (5.6 months). This extended period is needed because of the amount of time it takes a container to reach its destination (importer or distributor). Also the device has a very small format which allows it to be placed in a regular bubble mailer envelope which can be easily mailed by the regular postal service. Finally, the temperature and time information recorded by the device can be retrieved by any computer using an information retrieval device, to perform further analysis. A picture of the iButton and the information retrieval device can be observed in figure 56.

The process of instrumenting the shipments starts at the winery, where the person in charge of the instrumenting process initializes the iButton with software that we have provided. This software synchronizes the iButton clock with the computer clock and sets the iButton to record a temperature reading every 2 hours. At the same time the person fills out information about the shipment on the back of the mailer. This information is: Identification of the iButton, origin, date carton was tagged, container number, destination, horizontal and vertical position in container and the

Figure 56: DS1912G iButton and the information retrieval device.

type of container used (refrigerated, quilted or dry container). A picture of the back of the envelope, with the information required to be filled can be found in Figure 57. The device put inside the pre stamped bubble mailer, which is then inserted in a plastic adhesive bag along with instructions for the receiver. Finally, when the container is ready to be loaded with the pallets of wines, the plastic adhesive bag with the envelope, instructions and recording device is attached at the position indicated in the envelope. This is the end of the instrumenting process.

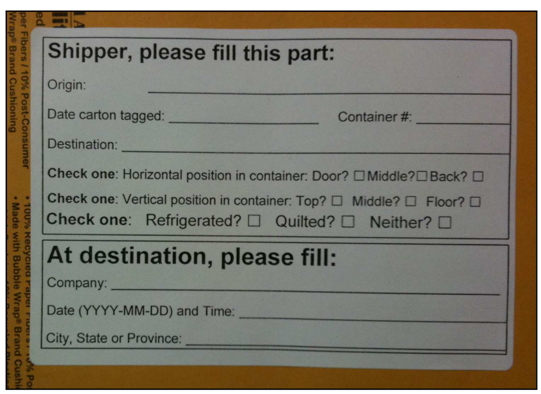


Figure 57: Information in back of envelope.

Some shipments are covered with a thermal blanket or liner to protect them from extreme temperature fluctuations. To determine the effect that this thermal blanket or liner has over the temperature, we set a device outside the blanket and one inside. The objective behind using two device in a shipment is to determine if there are any difference between them and if such a difference exists, how significant it is.

Once the container has departed, the winery relays the information of the ID of the iButton, container number, shipping company, vessel, route, destination, and estimated time of arrival by email to us. With this information we can access the shipping line website and obtain tracking information for the container. The information that we can retrieve is: date in which the container was loaded in the vessel; if transshipped, location and date that the container was unloaded and loaded into the new vessel and finally, date that the container was unloaded at the destination port.

Once the container arrives at the destination and is opened by the importer or distributor, he proceeds to recover each envelope with a device inside. He then fills out the remaining information on the back of the envelope: Company, date, time, and location (city and state) and mails the prestamped envelope (with the device inside) to us.

When we receive the envelope, using software that we have developed, we download the device information (temperature and date/time) into a database. At the same time we input the data located on the back of the envelope and the shipment tracking. The information we input is: origin and date/time of activation of the device, position in the container, container number, type of container, whether it was inside or outside the thermal blanket, container tracking information (loading, transshipment and unloading: place and date/time), and the destination and date/time of arrival. When all of the information has been recorded in the database and the device has been set to sleep, this marks the end of the instrumenting and tracking process.

The recording device is set inside the prestamped envelope, within the container. So our temperature readings represent the ambient temperature which happens inside the envelope, so there could be a level of distortion in the readings. We performed a number of test to determine if there is any significant difference between the temperatures of the outside air and those inside the envelope. Our results indicate that there can be a temperature differential of $\mp 1°$C between the inside and the outside temperature of the envelope. This differential is present when temperatures either increased or decreased rapidly, but after the temperature stabilizes the difference disappears in less than 2 hours, as the internal and external temperatures equalize. Therefore we can be confident that the temperature readings obtained inside the envelope are similar with those of the air temperature inside the container.

Our temperature recording device captures the air temperature inside the container and not the temperature of the liquid inside the bottle. This is important because we are interested in obtaining the temperature of the wine and the thermal inertia of the liquid can produce differences between the air and the liquid temperature. Butzke [22] indicates that there is a positive difference of $2-4°$C between the air temperature outside and the liquid, with this temperature differential we can be more confident that using the air temperature is a good representation of the liquid temperature. We did not perform any test to determine the air and liquid temperature differential.

APPENDIX B

BOTTLING DETAILED COMPUTATIONAL RESULTS APPENDIX

B.1 Complete instaces results

Table 36: Relative total costs of model and algorithm for each instance size.

Instance	Planned	Full Model				Algorithm			
		Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S1	100.00%	72.57%	84.59%	77.24%	84.92%	70.34%	73.56%	79.92%	84.18%
S2	100.00%	63.36%	70.33%	65.54%	68.77%	61.43%	73.43%	68.52%	74.31%
S3	100.00%	87.69%	92.59%	88.88%	94.27%	86.79%	95.11%	90.81%	96.54%
M1	100.00%	71.77%	77.18%	72.32%	79.94%	70.75%	70.97%	72.43%	83.10%
M2	100.00%	79.59%	90.59%	78.07%	93.94%	75.73%	84.21%	81.75%	81.05%
M3	100.00%	78.35%	85.62%	79.54%	85.19%	73.32%	76.55%	78.99%	81.83%
L1	100.00%	-	-	-	-	73.17%	79.16%	89.69%	86.18%
L2	100.00%	-	-	-	-	77.13%	77.13%	74.38%	81.20%
L3	100.00%	-	-	-	-	68.06%	73.88%	72.43%	81.66%
L4	100.00%	-	-	-	-	69.56%	78.08%	74.70%	90.53%
L5	100.00%	-	-	-	-	65.17%	72.92%	70.57%	76.66%
L6	100.00%	-	-	-	-	71.84%	80.03%	88.36%	87.10%
L7	100.00%	-	-	-	-	71.69%	78.95%	84.34%	91.79%

Table 37: Production parameters for each instance.

Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S1	Shifts	107	83	85	84	85	84	86	79	80
S1	% Setup Time	17.42%	13.31%	17.15%	15.19%	17.83%	11.37%	11.66%	17.76%	18.88%
S1	% Idle Time	27.98%	9.68%	9.94%	10.02%	10.71%	9.45%	10.63%	6.82%	6.67%
S1	% Over Time	1.14%	0.01%	0.33%	0.20%	0.34%	0.01%	0.01%	0.01%	0.01%
S2	Shifts	109	84	85	87	86	88	83	81	84
S2	% Setup Time	23.10%	14.21%	17.69%	14.73%	16.10%	11.96%	19.85%	18.19%	19.02%
S2	% Idle Time	26.37%	8.46%	10.59%	11.66%	10.52%	12.26%	10.36%	6.20%	8.04%
S2	% Over Time	1.82%	0.28%	0.12%	0.10%	0.17%	0.00%	3.50%	1.00%	0.01%
S3	Shifts	88	77	76	77	76	76	76	72	71
S3	% Setup Time	11.46%	11.94%	13.41%	12.13%	13.65%	12.00%	14.46%	14.74%	15.74%
S3	% Idle Time	22.77%	13.08%	10.81%	12.27%	10.57%	12.20%	10.94%	7.76%	6.28%
S3	% Over Time	3.09%	0.12%	0.20%	0.01%	0.23%	0.01%	0.01%	0.01%	0.04%
M1	Shifts	205	152	155	154	158	151	153	153	154
M1	% Setup Time	14.01%	11.38%	13.15%	12.24%	14.30%	10.24%	10.69%	13.08%	17.85%
M1	% Idle Time	29.77%	8.23%	8.67%	8.20%	10.85%	8.38%	6.35%	7.73%	9.77%
M1	% Over Time	1.68%	0.32%	0.43%	0.20%	0.36%	0.00%	0.02%	0.68%	2.65%
M2	Shifts	222	-	-	-	-	176	161	168	176
M2	% Setup Time	15.40%	-	-	-	-	13.11%	22.15%	19.34%	15.68%
M2	% Idle Time	27.29%	-	-	-	-	10.68%	9.71%	9.75%	9.85%
M2	% Over Time	1.82%	-	-	-	-	0.00%	8.55%	4.96%	0.05%
M3	Shifts	219	-	-	-	-	171	174	165	171
M3	% Setup Time	12.05%	-	-	-	-	9.18%	10.05%	14.85%	12.61%
M3	% Idle Time	25.67%	-	-	-	-	7.58%	7.80%	7.98%	7.28%

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Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
M3	% Over Time	2.45%	-	-	-	-	0.02%	0.03%	3.91%	0.07%
L1	Shifts	409	-	-	-	-	315	316	288	321
L1	% Setup Time	13.52%	-	-	-	-	7.78%	10.02%	25.59%	15.40%
L1	% Idle Time	26.75%	-	-	-	-	5.02%	6.14%	7.39%	8.16%
L1	% Over Time	1.04%	-	-	-	-	0.07%	0.09%	11.40%	0.06%
L2	Shifts	420	-	-	-	-	314	314	307	309
L2	% Setup Time	13.90%	-	-	-	-	9.97%	9.97%	12.52%	14.05%
L2	% Idle Time	29.75%	-	-	-	-	6.66%	6.66%	5.17%	6.47%
L2	% Over Time	1.31%	-	-	-	-	0.05%	0.05%	0.11%	0.09%
L3	Shifts	427	-	-	-	-	328	332	327	326
L3	% Setup Time	16.41%	-	-	-	-	7.44%	9.01%	11.90%	13.59%
L3	% Idle Time	31.63%	-	-	-	-	4.80%	6.31%	5.64%	5.90%
L3	% Over Time	2.21%	-	-	-	-	0.05%	0.09%	0.03%	0.08%
L4	Shifts	419	-	-	-	-	333	332	334	327
L4	% Setup Time	12.67%	-	-	-	-	8.30%	11.69%	12.71%	16.59%
L4	% Idle Time	23.66%	-	-	-	-	6.46%	5.99%	5.32%	5.54%
L4	% Over Time	1.58%	-	-	-	-	0.02%	0.04%	0.08%	0.01%
L5	Shifts	372	-	-	-	-	311	317	312	317
L5	% Setup Time	12.73%	-	-	-	-	8.12%	11.62%	13.73%	14.21%
L5	% Idle Time	20.55%	-	-	-	-	4.42%	7.30%	5.37%	6.57%
L5	% Over Time	1.72%	-	-	-	-	0.05%	0.05%	0.02%	0.05%
L6	Shifts	332	-	-	-	-	308	317	301	306
L6	% Setup Time	15.10%	-	-	-	-	7.68%	10.77%	13.21%	15.84%
L6	% Idle Time	15.40%	-	-	-	-	5.80%	6.45%	5.39%	6.57%

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Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
L6	% Over Time	2.19%	-	-	-	-	0.11%	0.10%	0.07%	0.08%
L7	Shifts	293	-	-	-	-	276	279	275	281
L7	% Setup Time	16.27%	-	-	-	-	8.94%	11.78%	13.17%	16.45%
L7	% Idle Time	11.59%	-	-	-	-	4.78%	6.41%	4.84%	6.25%
L7	% Over Time	1.67%	-	-	-	-	0.05%	0.08%	0.05%	0.20%

Table 38: Demand robustness parameters for each instance.

Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S1	Ave. % SS by OD	46.66	37.52	63.64	37.02	60.47	39.86	44.97	38.99	45.05
S1	% SKU below SS	45.76	50.85	1.69	47.46	1.69	50.85	20.34	49.15	16.95
S1	Days for 85%	3	3	2	3	2	3	2	3	2
S2	Ave. % SS by OD	34.21	45.76	65	39.8	91.54	43.82	58.73	43.57	55.24
S2	% SKU below SS	60.38	41.51	5.66	47.17	0	47.17	7.55	43.4	9.43
S2	Days for 85%	4	3	2	3	2	3	2	3	2
S3	Ave. % SS by OD	48.53	54.97	64.5	59.74	75.52	57.47	72.61	48.18	64.74
S3	% SKU below SS	47.83	39.13	4.2	34.78	0	30.43	2.17	47.83	6.52
S3	Days for 85%	3	2	1	3	1	2	1	3	1
M1	Ave. % SS by OD	50.57	36.79	58.25	27.92	57.92	45.72	41.59	40.74	41.65
M1	% SKU below SS	44.44	48.89	1.11	60	5.56	42.22	24.44	46.67	11.11
M1	Days for 85%	9	8	3	8	3	7	7	7	4
M2	Ave. % SS by OD	51.37	25.47	43.65	28.84	41.44	35.7	28.63	19.03	36.65
M2	% SKU below SS	57.81	64.8	11.2	64.8	34.4	57.48	66.14	75.59	18.11
M2	Days for 85%	9	9	4	9	8	9	10	10	4
M3	Ave. % SS by OD	43.9	25.39	47.41	31.65	16.54	33.4	38.77	28.74	37.73
M3	% SKU below SS	54.08	62.24	7.14	57.14	69.39	58.16	17.35	62.24	19.39
M3	Days for 85%	9	9	3	9	4	9	4	9	4
L1	Ave. % SS by OD	31.57	-	-	-	-	9.56	12.62	6.94	13.18
L1	% SKU below SS	61.29	-	-	-	-	87.63	53.76	89.25	46.24
L1	Days for 85%	17	-	-	-	-	18	18	20	18
L2	Ave. % SS by OD	27.25	-	-	-	-	9.54	9.54	3.41	13.2
L2	% SKU below SS	68.59	-	-	-	-	56.02	56.02	94.76	49.74

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Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
L2	Days for 85%	21	-	-	-	-	17	17	18	16
L3	Ave. % SS by OD	24.68	-	-	-	-	8.69	16.15	5.52	12.36
L3	% SKU below SS	68.32	-	-	-	-	88.12	50.99	90.59	60.2
L3	Days for 85%	20	-	-	-	-	21	17	21	17
L4	Ave. % SS by OD	19.77	-	-	-	-	7.38	8.82	3.01	12.18
L4	% SKU below SS	73.68	-	-	-	-	89.47	54.97	95.32	55.56
L4	Days for 85%	22	-	-	-	-	21	22	22	18
L5	Ave. % SS by OD	20.07	-	-	-	-	8.98	8.41	16.54	9.62
L5	% SKU below SS	74.35	-	-	-	-	87.96	56.02	78.53	53.93
L5	Days for 85%	22	-	-	-	-	21	26	19	22
L6	Ave. % SS by OD	31.33	-	-	-	-	4.57	8.67	1.91	13.71
L6	% SKU below SS	65.66	-	-	-	-	92.42	61.11	95.96	53.54
L6	Days for 85%	21	-	-	-	-	22	18	21	21
L7	Ave. % SS by OD	35.44	-	-	-	-	7.79	12.88	4.82	13.76
L7	% SKU below SS	62.5	-	-	-	-	85.62	51.88	93.12	53.12
L7	Days for 85%	16	-	-	-	-	17	17	18	17

Table 39: Capacity robustness parameters for each instance.

Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S1	Ave. Idle per quarter	59.88	16.07	16.90	16.83	18.21	15.88	18.28	10.78	10.67
S1	Est. Dev. Idle per quart	22.04	12.16	15.46	13.79	16.13	7.71	4.70	7.30	0.20
S1	Abs.Crew Change	19	15	22	17	20	14	21	9	9
S2	Ave. Idle per quarter	57.48	14.20	18.00	20.30	18.10	21.58	17.20	10.05	13.50
S2	Est. Dev. Idle per quart	13.74	7.01	13.44	8.41	17.30	4.63	11.73	7.52	0.18
S2	Abs.Crew Change	11	19	21	10	16	14	27	7	6
S3	Ave. Idle per quarter	40.08	20.14	16.44	18.90	16.07	18.54	16.64	11.18	8.91
S3	Est. Dev. Idle per quart	16.22	17.37	15.78	22.61	15.85	17.09	12.34	12.92	0.34
S3	Abs.Crew Change	8	7	7	7	7	18	18	6	3
M1	Ave. Idle per quarter	122.08	25.02	26.89	25.26	34.28	25.31	19.02	23.65	30.10
M1	Est. Dev. Idle per quart	48.63	14.33	23.34	18.47	36.74	20.60	17.05	18.84	0.13
M1	Abs.Crew Change	57	65	62	65	64	52	60	66	61
M2	Ave. Idle per quarter	121.15	35.91	29.55	33.28	27.54	37.59	31.28	32.77	34.69
M2	Est. Dev. Idle per quart	29.36	11.06	21.73	19.42	18.06	31.42	23.03	28.77	0.22
M2	Abs.Crew Change	66	70	65	71	65	46	62	64	43
M3	Ave. Idle per quarter	112.44	26.38	32.14	30.30	30.30	25.91	27.14	26.32	24.89
M3	Est. Dev. Idle per quart	35.45	12.26	26.76	19.22	23.51	11.21	20.93	17.72	0.16
M3	Abs.Crew Change	64	67	67	68	60	64	62	61	42
L1	Ave. Idle per quarter	218.78	-	-	-	-	31.62	38.83	42.56	52.40
L1	Est. Dev. Idle per quart	28.40	-	-	-	-	17.39	17.20	32.31	0.17
L1	Abs.Crew Change	169	-	-	-	-	135	143	137	125
L2	Ave. Idle per quarter	249.91	-	-	-	-	41.85	41.85	31.77	39.99
L2	Est. Dev. Idle per quart	51.34	-	-	-	-	25.34	25.34	41.77	0.15

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Instance	Parameter	Plan	Full Model				Algorithm			
			Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
L2	Abs.Crew Change	225	-	-	-	-	131	131	114	117
L3	Ave. Idle per quarter	270.10	-	-	-	-	31.52	41.87	36.87	38.48
L3	Est. Dev. Idle per quart	23.33	-	-	-	-	21.94	31.44	38.16	0.17
L3	Abs.Crew Change	217	-	-	-	-	131	139	126	129
L4	Ave. Idle per quarter	198.31	-	-	-	-	43.01	41.75	35.51	36.24
L4	Est. Dev. Idle per quart	25.96	-	-	-	-	25.11	17.33	36.24	0.12
L4	Abs.Crew Change	227	-	-	-	-	154	176	145	155
L5	Ave. Idle per quarter	152.89	-	-	-	-	27.52	46.28	33.49	41.69
L5	Est. Dev. Idle per quart	60.40	-	-	-	-	14.82	17.37	33.12	0.11
L5	Abs.Crew Change	205	-	-	-	-	123	131	114	131
L6	Ave. Idle per quarter	102.26	-	-	-	-	35.75	49.68	27.10	40.19
L6	Est. Dev. Idle per quart	51.07	-	-	-	-	18.49	21.10	21.02	0.14
L6	Abs.Crew Change	146	-	-	-	-	146	137	132	131
L7	Ave. Idle per quarter	67.90	-	-	-	-	26.37	35.75	26.65	35.14
L7	Est. Dev. Idle per quart	26.39	-	-	-	-	17.42	29.98	26.89	0.17
L7	Abs.Crew Change	131	-	-	-	-	129	144	115	124

Table 40: Running times (seconds) and optimal gap for each instance.

Instance	Parameter	Full Model				Algorithm			
		Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S1	Time (sec.)	3200	3200	3200	3200	233	692	877	851
S1	gap (%) *	3.40%	5.10%	4.15%	4.10%	1.10%	1.30%	1.19%	1.80%
S2	Time (sec.)	3200	3200	3200	3200	387	640	1167	1164
S2	gap (%) *	5.96%	5.56%	5.48%	4.72%	2.90%	2.90%	1.77%	1.39%
S3	Time (sec.)	3200	3200	3200	3200	392	633	505	647
S3	gap (%) *	3.21%	3.54%	3.96%	4.39%	1.20%	1.40%	2.64%	1.22%
M1	Time (sec.)	7200	7200	7200	7200	430	689	424	800
M1	gap (%) *	3.88%	4.15%	5.20%	8.10%	2.60%	1.50%	2.09%	1.67%
M2	Time (sec.)	7200	7200	7200	7200	432	746	585	1211
M2	gap (%) *	9.34%	20.04%	8.40%	32.43%	2.64%	6.39%	1.45%	2.45%
M3	Time (sec.)	7200	7200	7200	7200	277	640	475	1576
M3	gap (%) *	7.80%	7.92%	7.55%	16.10%	2.12%	3.27%	3.95%	2.91%
L1	Time (sec.)	-	-	-	-	444	750	2477	1237
L1	gap (%) *	-	-	-	-	2.75%	3.30%	2.99%	1.10%
L2	Time (sec.)	-	-	-	-	488	720	2405	2317
L2	gap (%) *	-	-	-	-	1.00%	1.68%	1.44%	2.36%
L3	Time (sec.)	-	-	-	-	447	655	2477	3122
L3	gap (%) *	-	-	-	-	2.41%	1.40%	2.61%	1.32%
L4	Time (sec.)	-	-	-	-	550	1164	2560	3081
L4	gap (%) *	-	-	-	-	2.91%	1.28%	2.79%	2.69%
L5	Time (sec.)	-	-	-	-	416	740	2453	2630
L5	gap (%) *	-	-	-	-	2.30%	2.64%	2.17%	1.44%

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Instance	Parameter	Full Model				Algorithm			
		Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
L6	Time (sec.)	-	-	-	-	445	785	3110	3207
L6	gap (%) *	-	-	-	-	1.12%	2.11%	4.90%	2.17%
L7	Time (sec.)	-	-	-	-	950	1000	2488	2374
L7	gap (%) *	-	-	-	-	1.00%	2.80%	2.65%	2.99%

Table 41: Run time (seconds) and optimal gap by instance.

Instance	Parameter	Full Model				Algorithm			
		Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
S1	Time (sec.)	3200	3200	3200	3200	233	692	877	851
S1	gap (%) *	3.40%	5.10%	4.15%	4.10%	1.10%	1.30%	1.19%	1.80%
S2	Time (sec.)	3200	3200	3200	3200	387	640	1167	1164
S2	gap (%) *	5.96%	5.56%	5.48%	4.72%	2.90%	2.90%	1.77%	1.39%
S3	Time (sec.)	3200	3200	3200	3200	392	633	505	647
S3	gap (%) *	3.21%	3.54%	3.96%	4.39%	1.20%	1.40%	2.64%	1.22%
M1	Time (sec.)	7200	7200	7200	7200	430	689	424	800
M1	gap (%) *	3.88%	4.15%	5.20%	8.10%	2.60%	1.50%	2.09%	1.67%
M2	Time (sec.)	7200	7200	7200	7200	432	746	585	1211
M2	gap (%) *	9.34%	20.04%	8.40%	32.43%	2.64%	6.39%	1.45%	2.45%
M3	Time (sec.)	7200	7200	7200	7200	277	640	475	1576
M3	gap (%) *	7.80%	7.92%	7.55%	16.10%	2.12%	3.27%	3.95%	2.91%
L1	Time (sec.)	-	-	-	-	444	750	2477	1237
L1	gap (%) *	-	-	-	-	2.75%	3.30%	2.99%	1.10%
L2	Time (sec.)	-	-	-	-	488	720	2405	2317
L2	gap (%) *	-	-	-	-	1.00%	1.68%	1.44%	2.36%
L3	Time (sec.)	-	-	-	-	447	655	2477	3122
L3	gap (%) *	-	-	-	-	2.41%	1.40%	2.61%	1.32%
L4	Time (sec.)	-	-	-	-	550	1164	2560	3081
L4	gap (%) *	-	-	-	-	2.91%	1.28%	2.79%	2.69%
L5	Time (sec.)	-	-	-	-	416	740	2453	2630
L5	gap (%) *	-	-	-	-	2.30%	2.64%	2.17%	1.44%

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Instance	Parameter	Full Model				Algorithm			
		Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
L6	Time (sec.)	-	-	-	-	445	785	3110	3207
L6	gap (%) *	-	-	-	-	1.12%	2.11%	4.90%	2.17%
L7	Time (sec.)	-	-	-	-	950	1000	2488	2374
L7	gap (%) *	-	-	-	-	1.00%	2.80%	2.65%	2.99%

Table 42: Run time (seconds) for sequential and parallel algorithm.

Instance	Sequential Algorithm				Parallel Algorithm			
	Model F	Model D	Model C	Model B	Model F	Model D	Model C	Model B
L1	989	791	2487	2227	444	750	2477	1237
L2	1232	695	5588	3731	488	720	2405	2317
L3	1074	844	5673	5192	447	655	2477	3122
L4	742	2068	4998	4447	550	1164	2560	3081
L5	861	1079	2581	4687	416	740	2453	2630
L6	1041	3900	5782	5398	445	785	3110	3207
L7	899	1270	5697	2827	950	1000	2488	2374

APPENDIX C

INTERNATIONAL SHIPPING DECISION SUPPORT SYSTEM

Giving the winemaker or importer/distributor a tool to analyze and determine the temperature risk of shipping their wine on a specific shipping route and time will significantly improve the international logistics of wine. Currently, the person who makes that decision, such as the winemaker or importer/distributor, has little or no information or system which can help him to make the decision of when to ship their wine or which route to use. In most of the cases the selected route is the one with the lowest cost, which generally does not correspond to the lowest temperature danger route.

Also the winery and importer/distributor has a limited flexibility in the choice of shipping times and routes because of three reasons. First, each agent along the supply chain has commercial commitments with clients the product needs to be available at a given moment, reducing the time-frame in which the shipment can be made. Second, the ocean carriers might not have an ample offering of shipping services and frequencies for a give origin-destination. In most cases the carrier will have a weekly service [82], which reduces the number of shipping routes and also the potential time-frame in which it can take place. Third, the temperatures will not significantly vary from one week to the next, so in order to have a temperature differential, for a given route, the shipping moment need to be spaced apart.

A way to help in the decision making to take into account the risk along with the limited flexibility in the of the shipping time/route is to use the percentage increase of the chemical reaction speed as a proxy of the danger of a given time/route. Using this information the winery can evaluate and optimize their shipping decision by either selecting a different shipping route or by advancing or delaying the shipping time or a combination of both.

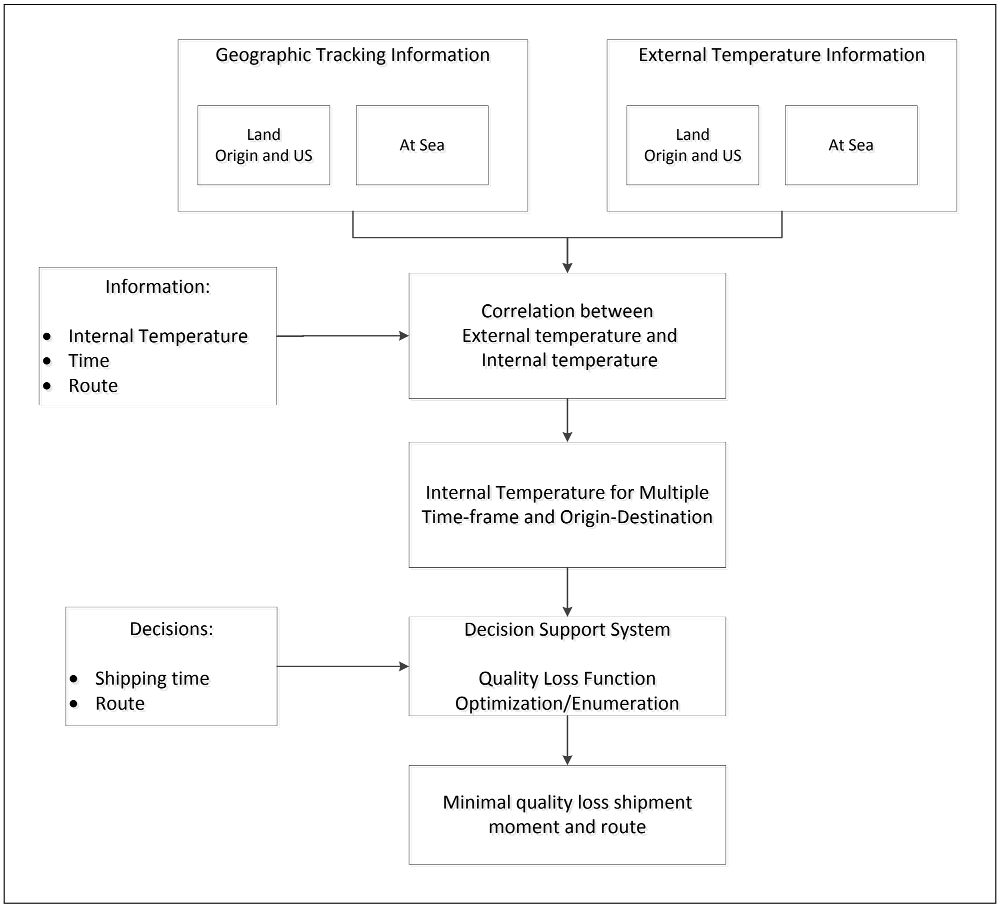

Figure 58: Structure of a international shipping decision support system that take into account the temperature quality loss.

Since its an impossible task to empirically determine the quality degradation for every route and time, we need to first device a mechanism in which we can correlate an available know temperature value, for multiple locations and times, with the internal container temperature. Figure 58 presents a proposed structure for an international shipping decision support system that takes into account the shipping moment and route to determine the danger of extreme temperature exposure. The objective of the system is to help the decision maker so he can determine the route and time that will reduce the extreme temperature danger for the wine.

TO construct such a system we need first to correlate the available external temperature information, for multiple times and locations, with the internal container temperature that we have been able to gather so far. Once we have obtained the correlation we can determine the internal container temperature for any shipping moment and route. Finally, for any given origin–destination and shipping time frame, using either optimization or extensive enumeration, we can determine the specific time and route that will minimize the temperature danger.

We will now describe the steps to develop the proposed decision support system:

1. **Source for external temperature data:** The US the National Oceanic and Atmospheric Administration (NOAA) has an extensive geographically positioned land based climate database were is possible to obtain the hourly and extreme temperatures. For the external temperature we will use the NCEP/NCAR Reanalysis 1 temperature data by Kalnay et al. [60] that uses multiple information sources and a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to the present. This allows to have 4 times a day surface global surface temperature on a 2.5° by 2.5° scale.

2. **Interpolation of geographic position for internal temperature:** Determine the location information for every internal temperature value. We have partial time and location information from the container tracking, we have: the origin, port of origin, unloading at transshipment port, loading at transshipment port, unloading at destination port and destination. With this information we can determine an approximate inland and sea route for the container and interpolate the approximate location of the container for every time and finally, relate this information with the internal container temperature.

3. **Statistical validation of external/internal temperature:** With the internal and external geo-referenced temperatures we can determine the correlation between them and analyze its statistical significance.

4. **Shipping time and route danger determination and optimization-enumeration for multiple time-frame and origin-destination:** Using the winery shipping time-frame and origin-destination of the cargo and route cost, we can determine the feasible routes and departure times. We can then determine for each route the external temperature with the available data and using the correlation factor we can infer the internal container temperature, quantifying the increase in the chemical reaction speed of each shipping moment and route. With these results, the decision maker, can select the route that conforms best with his specific needs of cost and risk.

C.1 Limitations of the decision support system

The limitations of the system come from two characteristics of the data and the model: First, the quality/granularity of the available temperature information and second, the ability to correlate the external temperature information with the internal container temperature.

The NCEP/NCAR Reanalysis temperature data uses multiple information sources and a state-of-the-art analysis/forecast system to obtain 4 surface temperature records per day on a 2.5° by 2.5° scale. The first limitation is that this source of data corresponds to a forecast that can be prone to the normal error that any forecast can have. The second limitation is the granularity of the data, our temperature records are in a 2 hour interval, while the NCEP/NCAR are in a 6 hour interval. We will either need to perform an interpolation of the NCEP/NCAR data or aggregate ours, in order to adjust the granularity of the information, with the subsequent data representation problems that come from the interpolation or aggregation of information.

The limitations that rise from correlating external with internal container temperature come from the fact that the container temperature depends on the position in which the container was placed in the vessel. From our observations we have seen that containers which are in the borders or in the top, directly exposed to sunlight, will have higher temperatures than the ones that are set inside the stack. We can also observe temperature differences among the containers that are not exposed to direct sunlight, which can be explained if the container is set below or over the deck of the vessel. We can even observe smaller temperature variations within the container. These temperature variations were also reported by the Xerox Corporation in a technical report by Leinberg [64].

Although there are temperature variations which are the result of the position in which the container was set, we can determine a worst case and an average temperature for the shipment, which can allow us to determine the quality loss for each case and help the decision maker. The worse case scenario is the one in which we are unable to determine a statistical significant correlation between the available external temperature with the internal one. This is because there is no possible solution to this limitation, but to search another more reliable source of external temperature information.

The quality/granularity limitation on the external temperature data is a significant limitation for the development of such a system, which is currently being explored. For the ability to correlate that information, because of the positioning of the container in the vessel, as it was indicated before: an average or worst case scenario can be used to display the potential risk to the decision maker.

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